URBAN FLOOD RISK HANDBOOK

ASSESSING RISK AND IDENTIFYING INTERVENTIONS

City Resilience Program
GFDRR
Global Facility for Disaster Reduction and Recovery
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Scott Ferguson | Mathijs van Ledden | Steven Rubinyi | Ana Campos | Tess Doeffinger

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Table of contents

LIST OF FIGURES

LIST OF CASE STUDIES

LIST OF TABLES

FOREWORD

Floods in urban areas are an important reminder of the vulnerability of our cities and the complex challenges they face in managing their growth and development. As urbanization continues to accelerate around the world, the impact of floods on densely populated areas is becoming more pronounced. Increasing pressure on the availability of urban land and space pushes urban development into low-lying river and coastal areas, often ignoring planning restrictions, disrupting natural processes, and placing more vulnerable people at greater risk. Global climate change exacerbates this challenge through increased precipitation, sea level rise, and other effects. Torrential rains, overwhelmed drainage systems, and inadequate planning systems have left cities confronting the consequences of more severe, frequent, destructive, and far-reaching inundations, affecting communities, infrastructure, and the environment. Making informed judgments about how to manage these risks is critical for a sustainable urban future.

To protect the growing concentrations of people and their assets in flood-prone urban areas, cities must make improvements in both flood mitigation and the maintenance and restoration of existing, aging, protective urban infrastructure. Determining the type of flood protection investments that are needed is a critical exercise that can influence the extent to which a city withstands and manages destructive floodwaters for years to come. To adopt a proactive and holistic approach to mitigate and adapt to urban flooding, cities must first conduct a **flood risk assessment.** That means evaluating the likelihood and extent of flooding, as well as the potential consequences and impacts of such an event. Though such assessments offer a wide range of possibilities in terms of resources required and detail produced, all involve developing a robust understanding of a city's current and future flood risk scenarios — where, why, and how. A good urban flood risk profile is the basis for the identification of different types of measures for flood risk protection, the formulation of policy recommendations and territorial plans, and the development of risk reduction strategies and solutions that are needed for a particular city.

This *Urban Flood Risk Handbook: Assessing Risk and Identifying Interventions* is a roadmap for conducting an urban flood risk assessment in any city in the world. It includes practical guidance for a flood risk assessment project, covering the key hazard and risk modeling stages as well as the evaluation of different flood-mitigating infrastructure intervention options and management of the project. The Handbook has been developed based on lessons learned from implementing urban flood risk assessments around the world in a diversity of contexts. It is intended for a wide variety of practitioners: project managers, city officials, and anyone else interested in conducting a strategic study of a city's flood risk and developing potential solutions for it. We expect this Handbook to contribute to the understanding of urban flood risk, make this specialized knowledge more accessible to a wider public, and support the process of building cities that are not only capable of withstanding floods but also provide safe, inclusive, and sustainable environments for all their residents.

Bernice Van Bronkhorst
Global Director
Urban, Disaster Risk Management, Resilience, and Land Global Practice
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ACKNOWLEDGMENTS

The ***Urban Flood Risk Handbook: Assessing Risks and Identifying Interventions*** was developed by the World Bank's City Resilience Program (CRP), within the Global Facility for Disaster Reduction and Recovery (GFDRR), under the leadership of Bernice von Bronkhorst, Global Director for Urban, Disaster Risk Management, Resilience, and Land, and GFDRR Practice Manager Niels Holm-Nielsen.

The coordination of this Handbook was provided by Steven Rubinyi and Ana Campos Garcia. The preparation of the Handbook was led by Scott Ferguson and Mathijs van Ledden. Tess Doeffinger was the technical editor.

The Handbook benefited greatly from World Bank colleagues, who provided valuable feedback in reviewing this Handbook—Brenden Jongman, Swarna Kazi, Dzung Huy Nguyen, Defne Osmanoglou, and Joop Stoutjesdijk—as well as from contributions from the following organizations: Deltares, Jeremy Benn Associates, and Royal HaskoningDHV.

For their help in developing the Handbook, we would like to thank Ross Eisenberg, Marc Forni, and Cristiano Giovando. For contributing to the conceptualization of the Handbook, we would like to thank Edward Anderson, Isabel Cantada, Lorenzo Carrera, Laurent Corroyer, Vivien Deparday, Eric Dickson, Stuart Fraser, Suranga Kahandawa, Yohannes Kesete, Lukas Loeschner, Lizardo Marulanda, Emma Phillips, Carolina Rogelis, Giovanni Prieto, Artessa Saldivar-Sali, Alanna Simpson, Diana Rubiano Vargas, Jian Vun, and Carmen Zena.

We would also like to thank Edward Anderson, Laurent Corroyer, Christian Vang Eghoff, Armando Guzman, Swarna Kazi, Yohannes Kesete, Linus Pott, Robert Reid, Artessa Saldivar-Sali, Jian Vun, and Jolanta Kryspin-Watson for providing suggestions and information on the technical case studies.

Mary Anderson edited the Handbook, and Estudio Relativo designed it.

The Handbook was made possible through funding from the Swiss State Secretariat for Economic Affairs, the Austrian Federal Ministry of Finance, and the City Resilience Program.

KEY TAKEAWAYS

The ***Urban Flood Risk Handbook*** offers a practical guide on how to conduct a broad-scale urban flood risk assessment and options appraisal. It is designed for project managers, practitioners, stakeholders, or anyone interested in carrying out a strategic study of urban flooding and potential mitigation solutions. The key takeaways from the handbook are described below, by chapter.

CHAPTER

1

DEFINING URBAN FLOOD RISK AND SCOPE

A clear understanding of the study's aim and scope from the start is essential and must include early involvement and input from all relevant stakeholders. This includes clearly defining the study's intended audience, the issue or issues it will address, and its geographical extent, recognizing the importance of choosing system boundaries (for example, including the relevant water systems when defining the study area).

Conscious and informed consideration must be given to the level of effort (time and cost) versus the overall accuracy and resolution required of the study, recognizing the important trade-off between the two but also remembering the law of diminishing returns: it is easy to get drawn into seeking perfection when simply a good job will suffice. A balance often is required when prioritizing what to include or leave out during the modeling process and assessment of options as well as what is required to support the objectives.

Stakeholder engagement should be central to the flood risk assessment and options appraisal, both to validate the development process and results and to help ensure uptake and support of the presented options and study outcomes. This engagement includes promoting the importance of integrated flood risk management solutions and ensuring that urban planning and development decisions incorporate flood risk analysis—which will not only reduce the negative impacts of flooding but also improve the living environment through as many societal and environmental co-benefits as practical.

CHAPTERS

2 and 3

FLOOD HAZARD ASSESSMENT AND FLOOD RISK ASSESSMENT

- Floods in urban areas can be caused by a variety of mechanisms including high river discharges, local rainfall, extreme tides, cyclone-induced storm surges, and severe wave overtopping. These potential drivers of flooding can occur independently, but several mechanisms can also be strongly dependent. Understanding the drivers of flooding and the possibility of joint occurrence in an urban area is essential in hazard modeling and risk assessment studies.
- The accuracy of the hazard and risk assessment depends heavily on the quality of underlying data. Data can be expensive and time-consuming to collect or purchase and must be considered as early as possible. Local data are always preferable but often hard to obtain in data-scarce environments. Freely available global data can be used instead with care.
- Sensible and robust hazard and risk results should be ensured through commonsense checks at key stages. These checks can be carried out by sufficiently experienced and knowledgeable personnel, particularly when adequate calibration or validation is not possible in data-poor environments, using global data if necessary to validate outputs. Remaining uncertainties in the hazard and risk assessment must be considered when evaluating interventions and clearly disclosed when communicating findings.

CHAPTER

4

EVALUATION OF INFRASTRUCTURE INTERVENTIONS

- An open-minded and structured approach to infrastructure interventions should be adopted—considering all potential interventions across the entire gray-green-blue spectrum as well as nonstructural options. The direct benefits (for example, reduced damage and fewer affected people) as well as the co-benefits of solutions should be evaluated and included.
- Hazard and risk modeling shall be set up with this wide range of options and with their benefits in mind so that these can be tested and evaluated. Interventions should be evaluated against the background of multiple future climate change and socioeconomic scenarios. In this way, robust solutions can be prioritized that can or will be effective in a large range of future situations. This often requires many simulations and can therefore be time-intensive—an important consideration during the planning and setup of the hazard and risk modeling process.
- Finally, full attention should be given to the potential interaction of interventions with each other, considering the possibility of negative impacts as well as cumulative benefits. Also, the environmental and social impacts of solutions should be considered early in the decision-making process to avoid potential pitfalls later. Potential resettlement and land acquisition are critical aspects to identify early on in this process.

CHAPTER

5

PROJECT MANAGEMENT ISSUES AND CLOSEOUT

- The development of well-structured and informative terms of reference (ToR), informed by local context, is an essential ingredient for a high-quality urban flood risk assessment. It is worth remembering that the ToRs should focus on output as much as possible and avoid specifying how to carry out every aspect of the assessment. This handbook provides some important lessons for developing a ToR document. A varied team is required to evaluate proposals because of the multidisciplinary nature of these assessments.

- A clear stakeholder management plan is an important tool in managing any project—particularly where multiple stakeholders may be involved—and the technical aspects of the work may be multidisciplinary, as is common with urban flood hazard studies and risk assessments. It is worth making this plan an early delivery from the consultants, and it should be considered a "live" document for the duration of the project, updated as necessary as the project progresses. Regular and frequent contact with the consultants and stakeholders throughout project execution is essential.

- A streamlined and thorough internal review process must be set out by the consultant and agreed upon by the client, with a clearly defined quality control and assurance process. This should include a formal client or stakeholder review and response process, which may involve more than one iteration, with a realistic time frame for each work stage or deliverable.

- Finally, a structured and thorough project closeout phase is essential to ensure the effective handover of all project deliverables; that the investments in data, models, and analysis are not lost; and that these deliverables are properly handed over. A properly handled closeout phase allows further development or reuse of the materials and promotes capacity building and continued technical development within local agencies or academia. To facilitate this, it is worth specifying the use of free and widely available software with no long-term or costly licensing requirements or implementing constraints for all technical aspects of the assessments.

The practical guidance provided in this handbook will further help improve urban flood risk assessments. The ultimate goal will always be to make the rapidly growing cities of the developing world safer and healthier places for people to live.

ABBREVIATIONS

EAD	expected annual damage
EM-DAT	Emergency Events Database
DTM	digital terrain model
GDP	gross domestic product
GIS	geographic information system
JRC	Joint Research Centre (European Commission)
LIDAR	light detection and ranging
MERIT	Multi-Error-Removed Improved-Terrain
MSL	mean sea level
NBS	nature-based solutions
O&M	operation and maintenance
OSM	OpenStreetMap
PDNA	post disaster needs assessment
SRTM	Shuttle Radar Topography Mission
ToR	terms of reference
3D	three-dimensional
2D	two-dimensional
1D	one-dimensional
0D	zero-dimensional

OVERVIEW

BACKGROUND AND OBJECTIVES

Cities around the world are following a common trend of increasing concentration of population and economic activities, often with little planning or forethought regarding the consequences of urbanization. It is expected that 70 percent of the global population will live in urban areas by 2050.[1] These densely built-up areas are increasingly vulnerable to flood disasters from a combination of increased runoff and increasing exposure of population, assets, and economic activities, with poor people disproportionally affected by these and other natural disasters (Hallegatte et al. 2020). Climate change and socioeconomic development are likely to exacerbate the problem as floods become more frequent and more severe.

By 2030, urban exposure to flooding will more than double (Güneralp, Güeralp, and Liu 2015). Yearly flood losses in 136 major cities around the world reached an estimated US$6 billion in 2005, but by 2050 yearly projected losses are estimated to increase to US$52 billion accounting only for socioeconomic changes and not factoring in subsidence or climate change (Hallegatte et al. 2013). National and municipal government agencies must therefore identify adaptation strategies and adopt sustainable, risk-informed investments to better manage urban flood risks if they are to minimize the misery and disruption that flooding brings, help reduce poverty, and achieve sustainable economic growth.

This handbook provides practical guidance on the setup and implementation of risk-based urban flood assessments to be carried out in collaboration with local stakeholders. The assessment methodologies have been addressed both in academic texts (Ashley et al. 2007; Zevenbergen et al. 2010) and by global organizations (Jha, Bloch, and Lamond 2012). This handbook offers complementary and contemporary knowledge on urban flood assessments, with a target audience of project managers, stakeholders, and anyone interested in conducting such assessments. Recent experiences and an in-depth review of recent urban flood risk assessments have been key ingredients in the creation of this handbook.

RISK MANAGEMENT PROJECT CYCLE AND STAGES

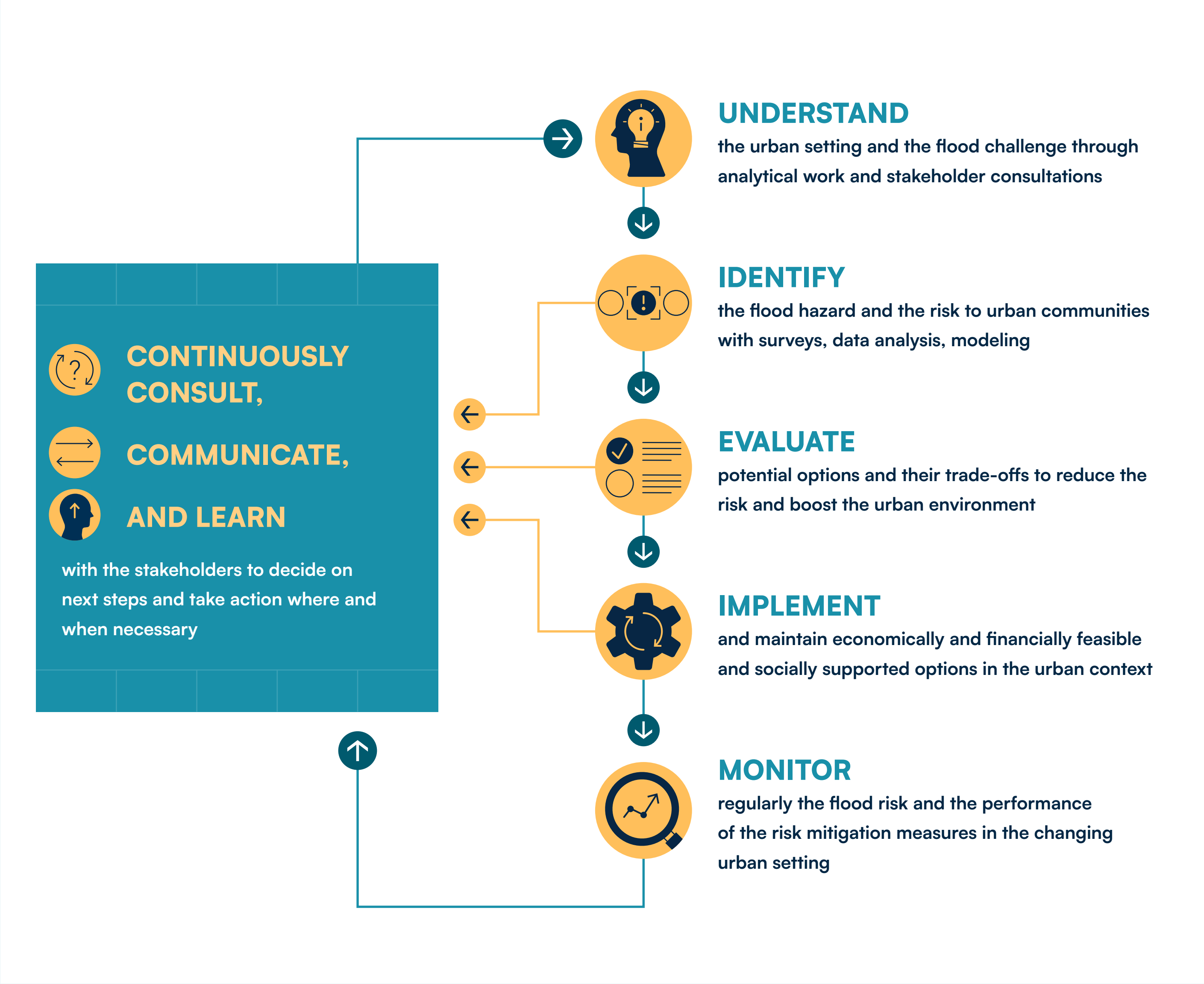
Urban flood risk assessments are often carried out during project identification and preparation to define the appropriate location, type, and size of flood management interventions and to support investment decisions by the potential financier or beneficiary (figure O.1). To converge on appropriate interventions, these assessments have three main elements: the flood hazard assessment, the flood risk assessment, and the evaluation of interventions. Myriad technical and nontechnical factors make these assessments a challenging puzzle, such as

Natural variability and different flood mechanisms, compounded by limited and often inaccurate data for calibration and validation of hazard models as well as uncertainties about climate change in the hazard assessment;

High density and rapid changes of population and assets, which cause uncertainties about socioeconomic change and urban footprint expansion in the risk assessment and lack of validation information about direct and indirect damages as well as impacts to population during floods; and

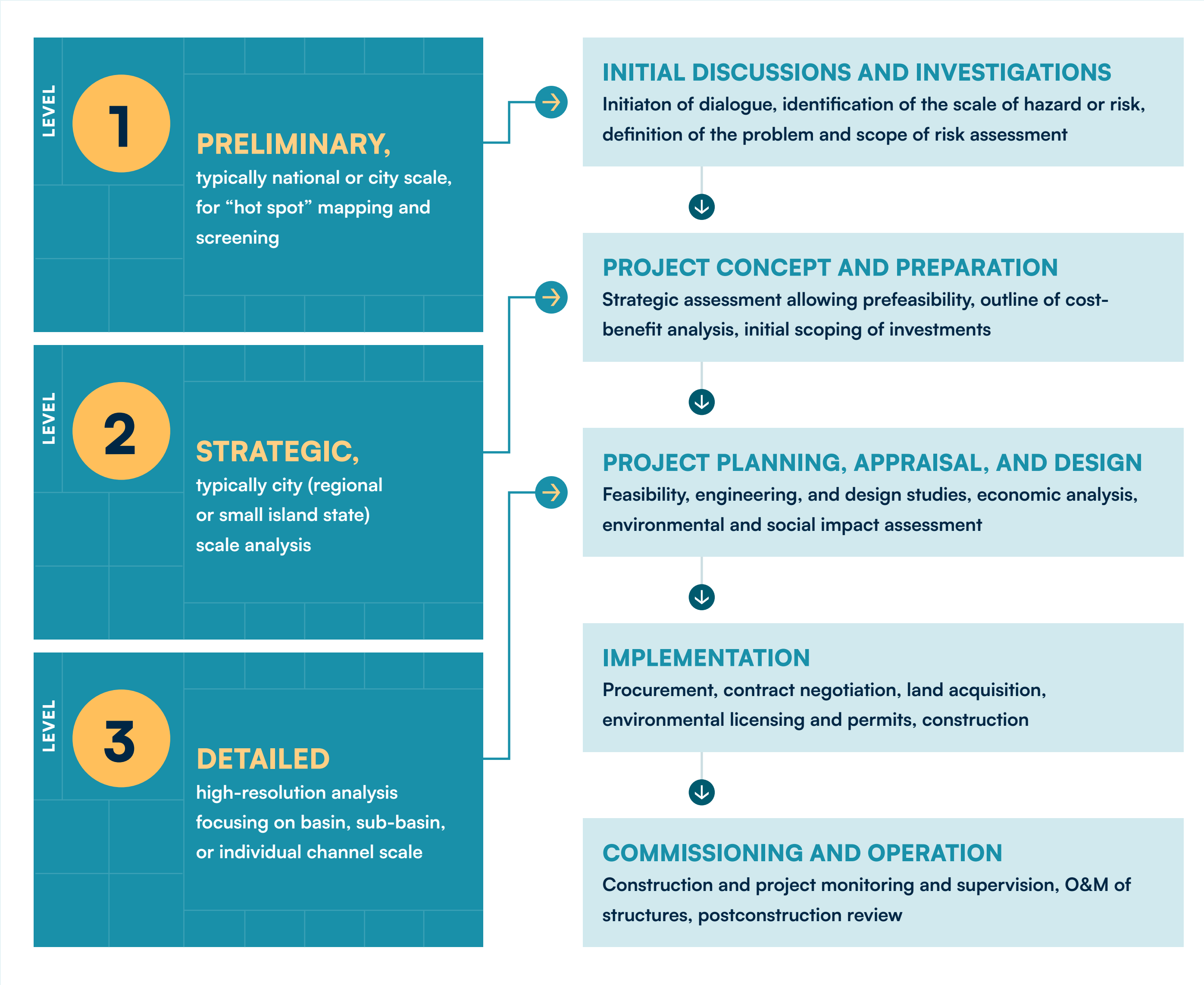
Implementation issues, such as choosing between numerous possible interventions, low planning and enforcement capacities, environmental and social impacts such as potential relocation, limited funding, and maintenance of the intervention.

Figure O.1 The Flood Risk Management Project Cycle



Different project stages require different levels of understanding, assessment, and decision-making (figure O.2) and therefore different levels of resolution and acceptable uncertainty within the data. This handbook distinguishes three levels of flood risk assessment—(1) preliminary, (2) strategic, and (3) detailed—recognizing that, in reality, many variants exist between the levels. At each level, the risk assessment is part of the project definition or design process but with a different level of detail tailored to the purpose of that specific project stage. The results may well be tailored to match the specific needs of the assessment. However, they tend to be similar in format regardless of the level of assessment.

Figure O.2 Typical Project Development Stages



Source: Adapted from Shah, Rahman, and Chowdhury 2017.

Note: O&M = operation and maintenance.

ORGANIZATION OF THE HANDBOOK

The focus of this handbook is mainly on Level 2 assessments for urban environments. In such an assessment, the general urban areas at risk and the type of flood hazard are reasonably well understood. However, the quantification of the hazard and risk and the screening and prioritization of potential options to reduce risk must be assessed to arrive at a potential package of interventions for further discussion with the beneficiaries. As mentioned previously, these assessments have three main elements: the flood hazard assessment, the flood risk assessment, and the evaluation of interventions. In addition, the overall project management of such an assessment typically begins by setting the project scope and is completed during the closeout phase of the project. Thus, this handbook focuses on five phases of a Level 2 assessment (figure O.3). The handbook describes in detail how to conduct such an assessment in the following five chapters:

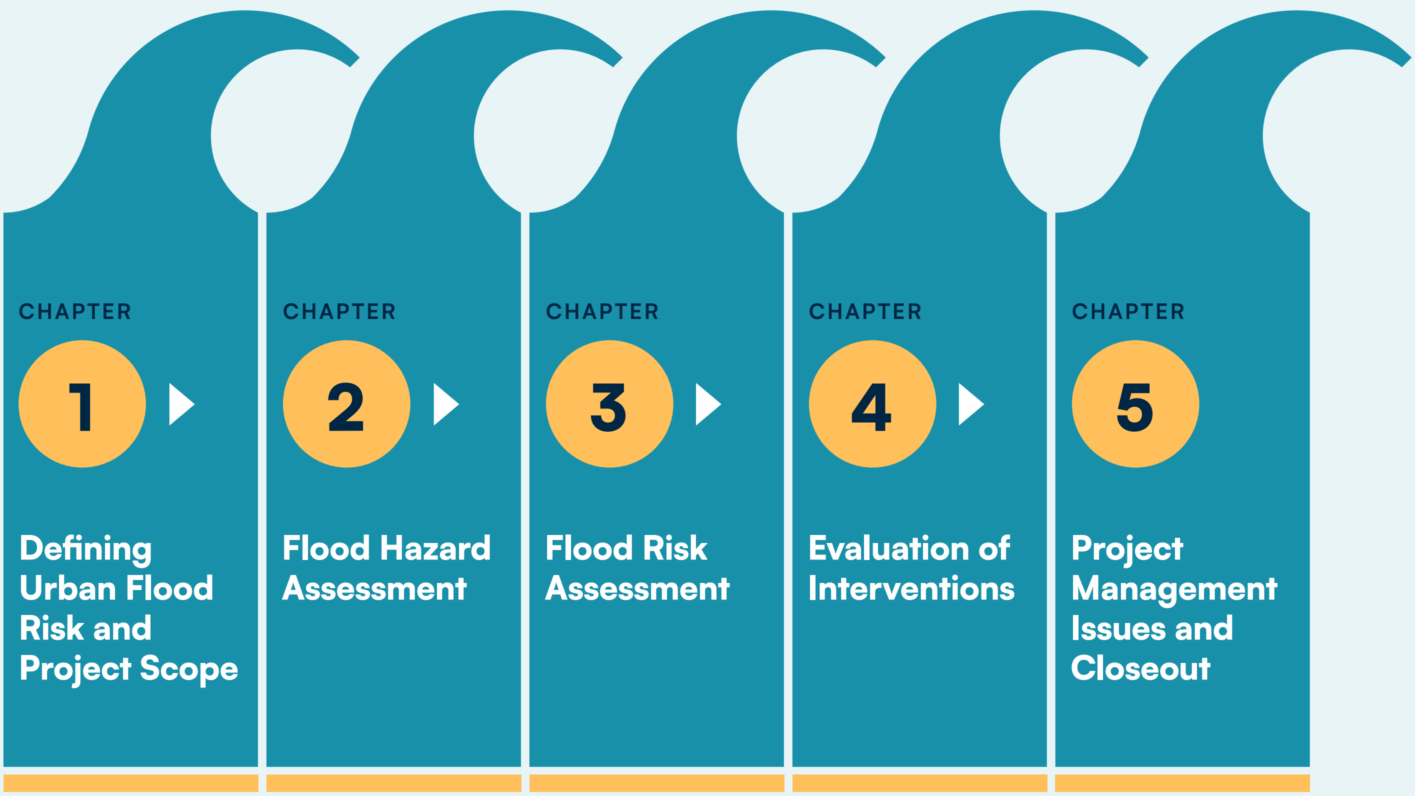
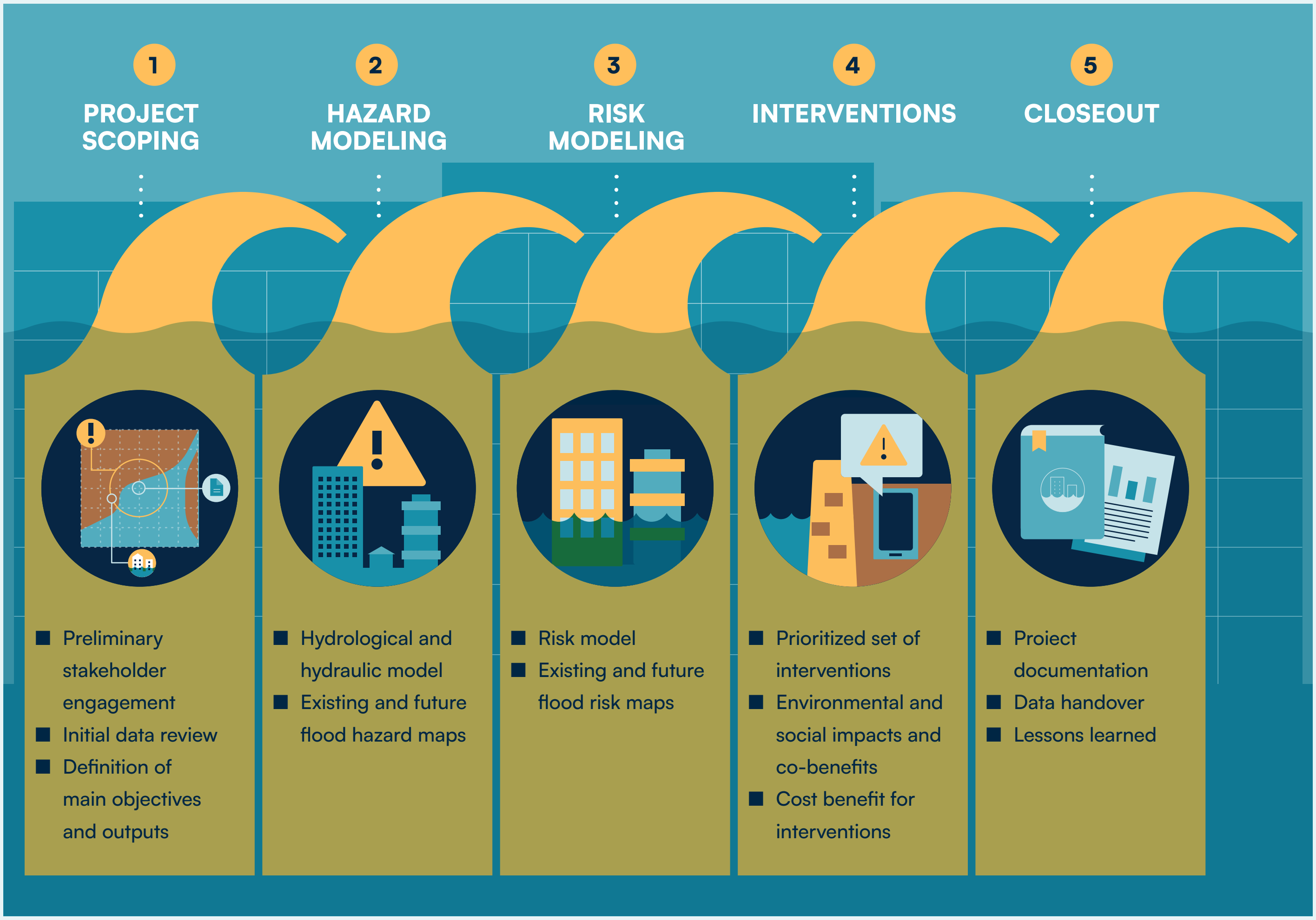


Figure 0.3 Five Phases of a Level 2 Urban Flood Risk Assessment



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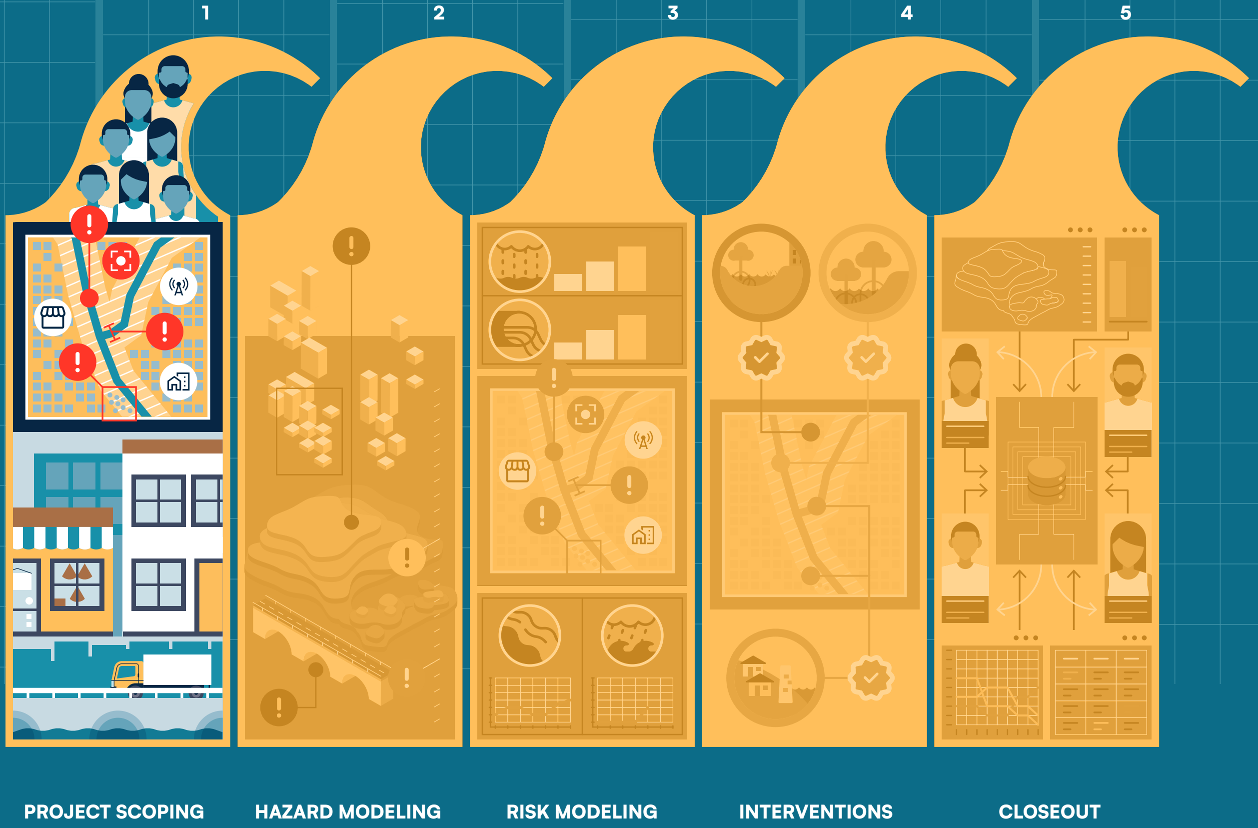
ENDNOTES

1 Urban population data are from the World Urbanization Prospects database of the United Nations Department of Economic and Social Affairs (accessed January 2022), https://population.un.org/wup/.

CHAPTER

DEFINING URBAN FLOOD RISK AND PROJECT SCOPE

1

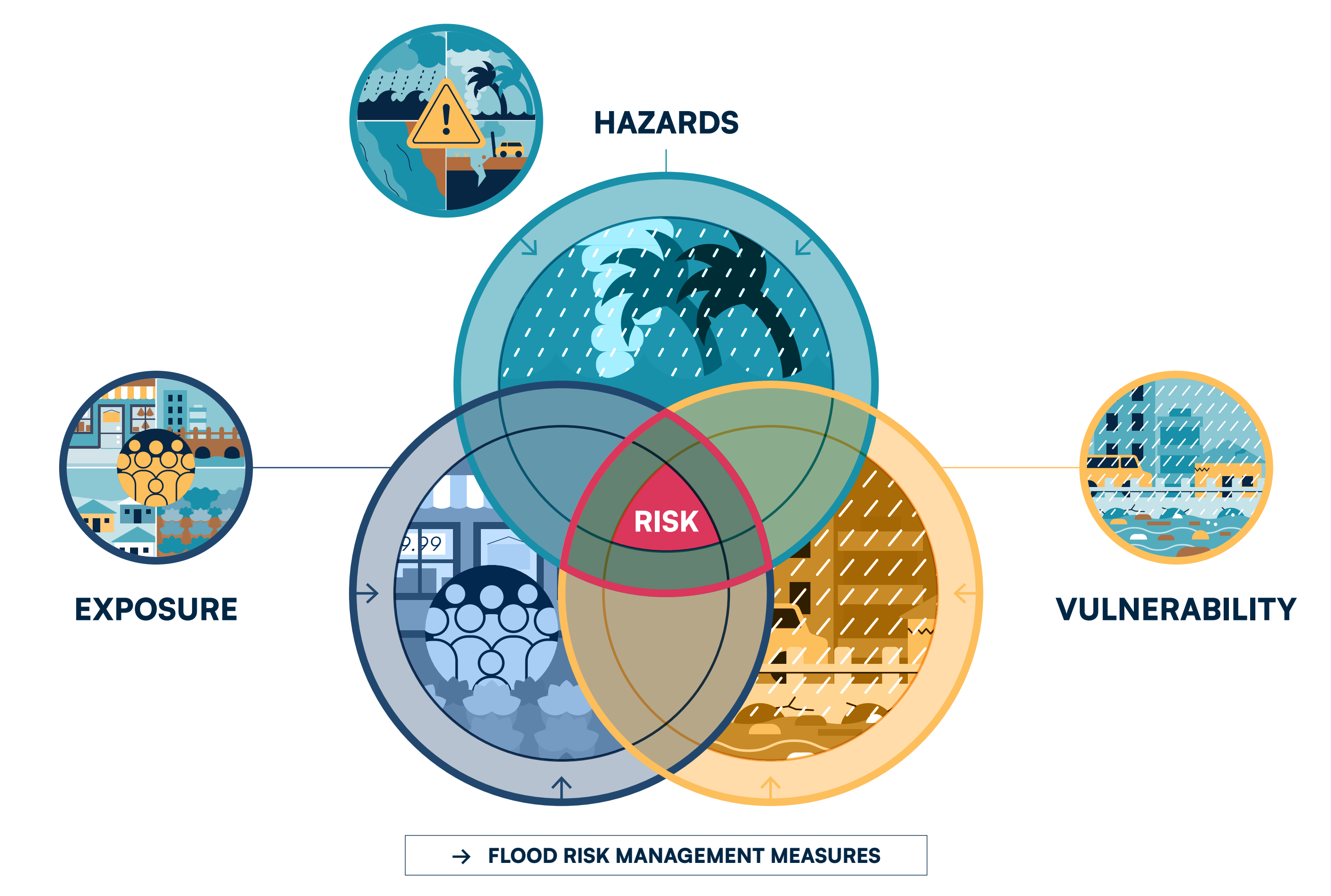


1.1

FLOOD RISKS DEFINED

Urban flood risk is “the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event” in an urban environment (EU 2007, chapter 1, article 2). This can be difficult to quantify, and many approaches to characterizing flood risk attempt to include many of the complex factors involved. In simple terms, however, urban flood risk can be considered as a function of hazard, exposure, and vulnerability—each of which is further described below. Figure 1.1 illustrates the interaction between these factors, particularly how a change in one or more of them will alter the resulting risk.

Figure 1.1 **Factors of Disaster Risk**



Hazards

Flood hazards in an urban environment can be caused by inundation from a wide range of sources, including the obvious ones such as ***coastal*** (including tidal, storm surge, or wave overtopping); ***fluvial*** (floodwater from a watercourse); and ***pluvial*** (floodwater that cannot or hasn't yet been able to get into a watercourse). Floods may also, in some circumstances, result from the failure or breach of man-made structures (such as dams or embankments) or natural defenses (for example, coastal ridge breached by shoreline erosion). Less obvious sources may include groundwater or snowmelt. Most often, however, there will be a combination of sources and mechanisms, which can often be analyzed independently from each other, but often must be considered jointly. Long-term trends—such as sea level rise, the possible change in rainfall intensity both upstream and locally, or future changes in cyclone characteristics—may exacerbate the frequency and magnitude of these hazards.

These hazardous events, although sometimes considered deterministic events, have a certain probability of occurrence now and in the future, in terms of both intensity and spatial distribution. Therefore, strictly speaking, hazards should be expressed or quantified in probabilistic terms (that is, with a measure of intensity and a likelihood of occurrence). True deterministic events are those events that have actually happened, such that for a given set of input conditions, there is a single (known) outcome—that is, the event that occurred.

Exposure

An urban area's exposure encompasses the entire inventory of elements and activities in the area that can be affected by the hazards. This inventory comprises

- The population and its assets such as homes and belongings, private businesses, and industrial assets;
- Infrastructure such as roads, drinking water, sanitation, drainage, and flood protection infrastructure;
- Public infrastructure like health care and school facilities;
- Environmental and cultural assets; and
- Economic activities.

Exposure is not static but dynamic in time, owing to, for example, changes in physical processes, socioeconomic growth, migration, and economic changes.

Vulnerability

Vulnerability refers to the degree to which exposed people and their livelihoods, along with additional items or activities such as infrastructure and natural assets, are adversely affected by a certain hazard (Cardona et al. 2012). Hazards can cause casualties, direct damage to assets, and disruption of services. The vulnerability of built infrastructure is often related to the engineering design and construction standards of these structures (for example, housing type and construction material). Differences in human and social vulnerability are, however, more complex to quantify because they are associated with the sociodemographic profile, livelihood strategies, strength of social networks, and households' access to basic services (Tran et al. 2021).

1.2

FLOOD RISK ASSESSMENT FRAMEWORK

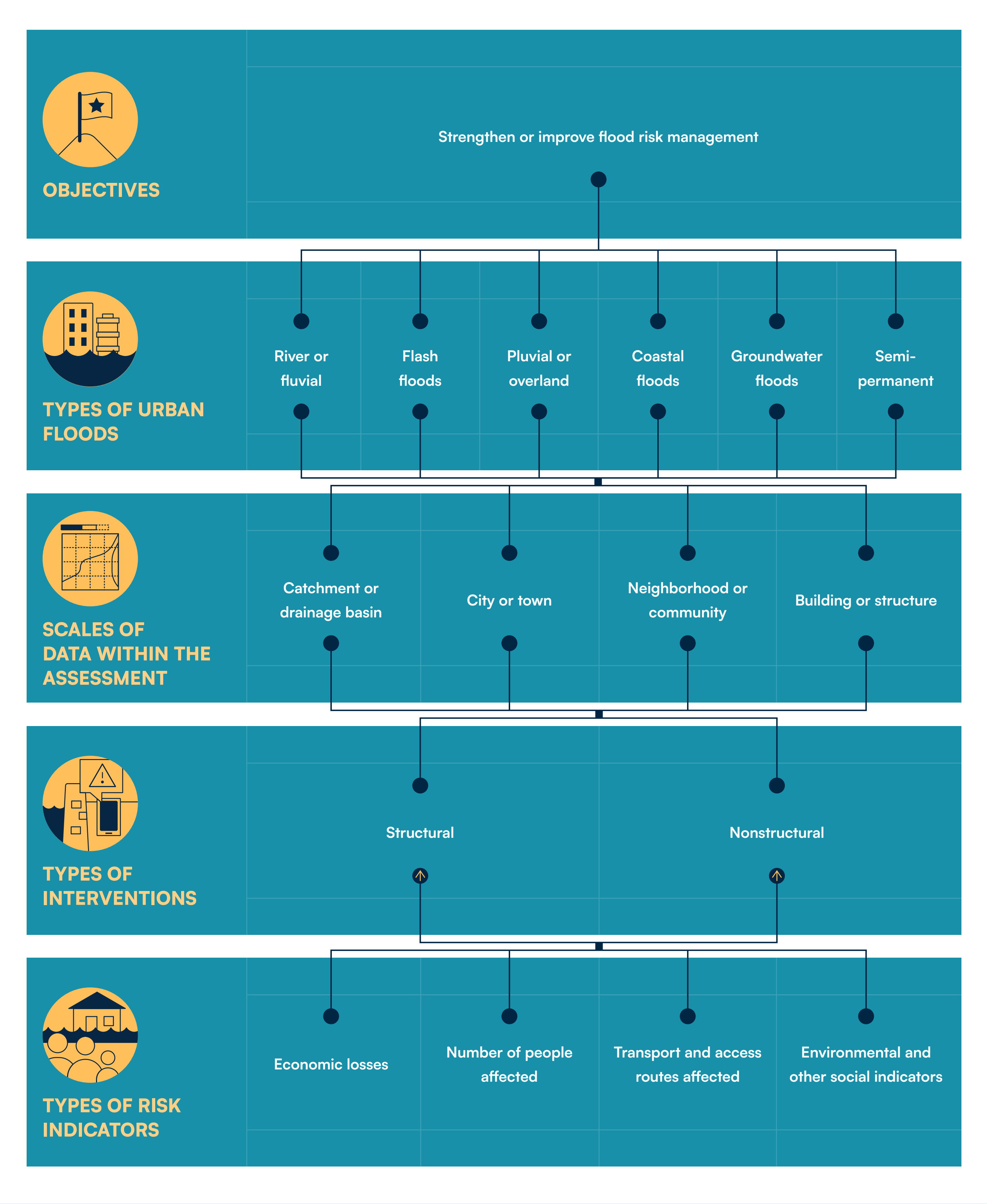
Flood risk management is achieved through interventions that are shown to be effective in the context of both current and future scenarios and the associated impacts. Before starting an urban flood risk assessment of this type, its scope must be properly defined by considering the following questions:

- **Which flood hazards and consequences are relevant in both the short and long term?**
- **Which analysis methodologies should be considered, and how will they influence the resolution, accuracy, and confidence levels?**
- **What is the spatial scale of the analysis and the type of intervention to be considered for reducing the risk?**
- **Recognizing that this analysis is principally aimed at the project concept and preparation stage, what are the main aims of the assessment?**
- **What existing data or models or analyses are already available that may help meet the aim or scope of the assessment, and what must be collected or developed?**
- **Who are the relevant stakeholders, and what is the institutional setting for existing risk management and future investment decisions?**

These questions are fundamental to establishing the scope of an urban flood risk assessment and must be considered prior to commissioning a study. Further refinement and consolidation may take place during the inception phase[1] of the assignment once the consultant has had a chance to better understand the context of the work, but any changes in the overall scope should be avoided once the assignment has begun. This scoping exercise should be done in close collaboration with stakeholders, who generally have a good knowledge of the issues and areas of concern and of past studies and intervention success. This is the first step of an assessment and will determine the overall success of the study.

Figure 1.2 provides a framework of key issues or factors that should typically be considered under a Level 2—that is, a strategic—flood risk assessment. It is useful to keep this framework in mind throughout the assessment, particularly when developing the documentation (the terms of reference) that will define the requirements for a procurement exercise. This framework contains the primary components that will determine the focus of the proposed assessment and must therefore be considered at an early stage. This framework can also act as a reminder throughout the assessment that will help ensure that the intended objectives, activities, and outcomes for the study are met. The various aspects of this framework are discussed in more detail later in the chapter. In addition to the items shown in figure 1.2, which focus mainly on the technical aspects of the analysis, it is important to have a grasp of the institutional mechanisms in place and the data and models that are available for the assessment.

Figure 1.2 Project Framework for a Level 2 Flood Risk Assessment



1.3 AIMS OF THE ASSESSMENT

The Level 2 assessment would normally follow a Level 1 (preliminary) study that will have highlighted the scale of flood risk, identified flood hot spots, framed the flood risk within the wider city-scale risk context, and provided a starting point for further discussion and a focus for additional studies. The purpose of the Level 2 assessment is to build on this preliminary understanding and develop sufficient knowledge, data, and outcome certainty to support strategic flood risk management decisions and investment planning. This assessment normally has several key aims, described below.

Develop or improve the baseline understanding of flooding in a city.

This includes the processes that result in flooding; the sources and pathways of flooding; and the people, assets, and infrastructure exposed to flooding (often referred to as the "receptors"). The assessment will begin to characterize the flood hazard by developing statistical information on the likely frequency of flooding or events of a particular severity—often referred to as "design storms" for extreme rainfall or as a "design hydrograph (level or flow)" for extreme river conditions or storm surge levels. It must be remembered that these design events do not represent specific events but reflect simulated conditions that may be expected to occur with a given frequency (often referred to as "return periods").

Develop sufficiently accurate and reliable flood hazard data.

To cover a wide range of strategic planning activities, the data will include, if possible, maps of sufficient resolution to enable the identification of individual buildings and assets that may flood. These maps will depict inundation depths and extent (usually in the form of gridded water depth) for different return periods based on hydrological assessment and hydraulic modeling of the urban area and surrounding catchment areas that drain into or through the urban area.

Quantify flood risk in a meaningful way.

Quantification of risk supports the analysis, prioritization, justification, and selection of mitigation options, ensuring that the decisions made are both robust and defendable. It can incorporate different aspects of risk, such as the impact on buildings and contents, the numbers and susceptibility of the affected population, the damage to other assets and infrastructure, and economic losses as well as the negative environmental impact that often accompanies urban floods. Quantification of risk is vitally important to provide a basis for assessing the benefits of interventions, allowing for the cost-effective use of often limited resources.

Develop and test a range of mitigation options and adaptation strategies under a range of potential scenarios.

The hazard and risk modeling framework should evaluate these options and strategies, which may comprise both structural and nonstructural interventions. Structural interventions should include the full array of gray, green, and blue interventions, in which the green-blue options are often also referred to as "nature-based solutions."[2] These interventions should be implemented within the models where possible and tested against a range of both current and future scenarios to assess their effectiveness and benefits against an agreed-upon set of objectives.

Prepare an investment plan.

The plan should identify short-, medium-, and long-term sustainable investments with a focus on integrated and interagency flood risk management. To prioritize interventions as part of this investment plan, an initial evaluation of the costs and benefits as well as the potential environmental and social impacts shall be carried out. Stakeholder input is of particular importance in this step to ensure sensible and achievable options and achieve full support and buy-in for the investment plan proposal.

Create a vehicle for improving government engagement.

Engagement with stakeholders can build capacity and create a springboard for further promotion of integrated sustainable urban development initiatives. The creation of flood hazard and risk maps, as well as the discussions about potential interventions, provide unique opportunities to engage stakeholders, generate a common understanding of the flood issues, and generate support for interventions to increase urban resilience.

1.4 TYPES OF FLOOD HAZARDS

Urban floods can have very different characteristics. For example, the urban flood of New Orleans after Hurricane Katrina in 2005 resulted from a hurricane-driven storm surge and subsequent failure of the embankment system around the city. Bangkok flooded in 2011 because the Chao Phraya River system had insufficient capacity to contain the high river flows upstream of the city. The floods of Jakarta in 2021 resulted from heavy monsoon rains and affected tens of thousands of people. The various origins of flooding aside, other factors such as variations in spatial terrain elevation may result in very different urban flood behavior.

It is clear from these historical events that it is important to understand the characteristics of the specific flood events because they can be quite different and will require different approaches. Some key relevant considerations include

- ***Origins*** of the flooding, such as direct rainfall, large rivers, coasts, inland lakes, mountainous regions, and groundwater;
- ***Causes*** of the flooding—from blockages, erosion, breaches, or structural failure (dam or dike failure; glacial lake outburst flood, commonly referred to as "GLOF"; dune breaches; and so on) to lack of drainage capacity;
- ***Geography*** of the receiving area, which could be steep, flat, or constrained and could also exhibit natural or human-induced subsidence;
- ***Speed of flooding onset,*** which could be rapid with little warning or slow with ample warning; and
- ***Joint occurrence of landslides*** including debris and mudslides.

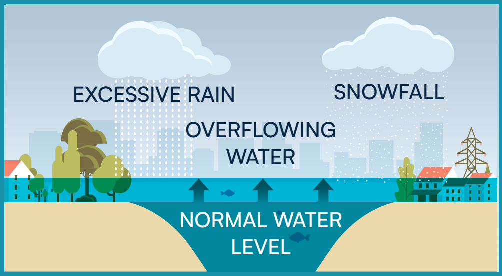
This handbook addresses four primary types of urban flooding: river or fluvial floods, pluvial floods, coastal floods, and flash floods (figure 1.3). Each flood hazard requires a different modeling approach that contains some common aspects but also key technical differences. It is important to be aware that a flood hazard may also become more significant under future conditions—for example, in low-lying coastal areas because of sea level rise or in some cases exacerbated by land subsidence. Such areas may not only suffer more coastal flooding but also become more prone to pluvial flooding because of drainage issues resulting from the higher sea levels.

Figure 1.3 Four Common Types of Floods and Their Causes

1 RIVER OR FLUVIAL FLOODS

Insufficient capacity and/ or protection during high discharge, resulting in overflow into urban areas

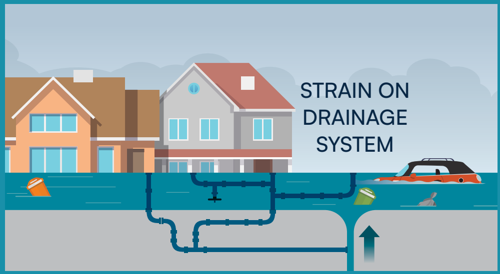
Examples:
Bangkok, 2011;
Mississippi River flood, 2019



2 PLUVIAL FLOODS

Insufficient capacity of the urban drainage system during rainfall events, resulting in flooded urban areas

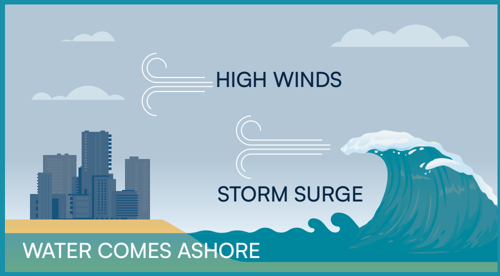
Examples:
Houston, 2017;
Paramaribo, Suriname, 2022



3 COASTAL FLOODS

Inundation of low-lying land by tidal water during storms (cyclones, extratropical storms), resulting in flooding in the city

Examples:
New Orleans, 2005;
Beira, Mozambique, 2019



4 FLASH FLOODS

Rapid onset of damaging flooding due to intense rainfall run-off from nearby hilly terrain and/or a dam or dike breach

Examples:
Brumadinho Dam, Brazil, 2019;
Germany, Belgium, and the Netherlands, 2021

Source: Adapted from Zurich 2020.

It is essential to recognize that the different urban flood types can have important interactions and that compound flood events (that is, combinations of flood mechanisms) may be relevant to consider during the assessment (Bevacqua et al. 2019; Valle-Levinson, Olabarrieta, and Heilman 2020). For example, a low-lying city near the coast with a gravity-based drainage system may face predominantly pluvial floods. However, the impact of pluvial flooding can be much more severe if this event coincides with a high water level at sea due to storms or during spring tides. Also, future sea level rise and increased rainfall amounts or intensity may place further pressure on the capacity of the urban drainage system. As these examples highlight, such interactions should be identified during scoping of the urban flood risk assessment and an appropriate modeling approach tailored accordingly.

1.5 TYPES OF CONSEQUENCES

Urban floods may result in very different consequences depending on the density of the built-up area and the wide variety of urban activities that may take place. Flooding has four primary types of consequences (figure 1.4), but these consequences can be very different because of variations in the three main risk factors identified earlier:

Hazards, by type of flood and characteristics of flooding—for example, water depth and velocity but also the duration of flooding, speed of onset, and water quality (such as salinity, chemical waste, and sewage);

Exposure of the urban area and its population, economic activities, and environmental and cultural heritage; and

Vulnerability of the affected people and assets, which is especially relevant in cities of low- and middle-income countries, where rich and poor neighborhoods may live side by side.

In addition, it is important to be aware that consequences can also vary in the future owing to future urban growth, industrialization, or climate change. Each consequence requires a different approach—having some common aspects but technical differences in modeling.

Figure 1.4 Consequences of Flooding, by Type

1

HARM TO PEOPLE

- Deaths, injuries, other health impacts (from large flow depth or high flow velocities), and displacement (from large flood extent and long duration)

Ethiopia, October 2018

2

DAMAGE TO ASSETS

- Direct damage to assets such as buildings (such as homes, markets, schools); infrastructure (such as bridges); agricultural crops; industrial facilities and so on

Sudan, October 2020

3

ECONOMIC LOSSES AND SOCIAL IMPACTS

- Interruption of economic activities (such as power outages, water supply interruptions, access restrictions and so on), job losses, poverty increase

Lao PDR, August 2018

4

ENVIRONMENTAL AND CULTURAL DAMAGE

- Leaks of polluted substances (such as oil), damage of cultural sites (such as religious sites, museums)

Sierra Leone, August 2017

Photos: © World Bank.

Covering all relevant consequences for a specific urban context in a Level 2 assignment is paramount. The direct damage of floods to assets such as buildings and infrastructure is an obvious and well-known consequence in all urban environments, and there are various methods to quantify these damages. However, the indirect economic losses and also environmental and cultural damage can be significant consequences of floods. Hence, these must also be investigated with sufficient detail despite the challenges to precisely quantifying these consequences. Finally, it is also important to realize that some consequences can be sensitive (for example, loss of life or damage of cultural heritage) and thus should be handled with care in discussions with the stakeholders.

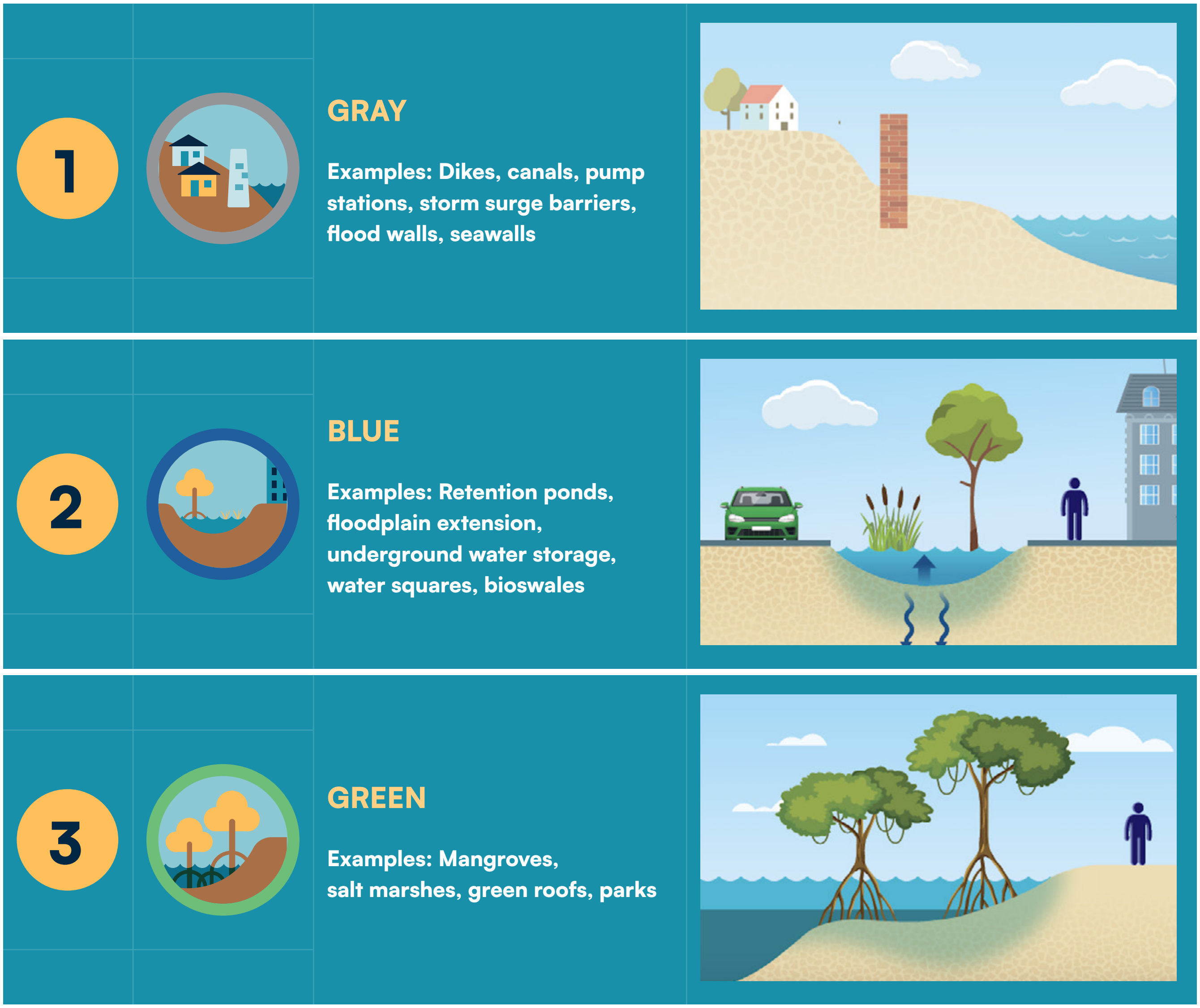
1.6 TYPES OF INTERVENTIONS

Many interventions are available for urban areas, and there are several different ways to classify them. One of the primary means of classification is between structural and nonstructural interventions.

Structural interventions for urban areas include, for example, dikes or storm surge barriers as well as bioswales and retention areas. These are often also referred to as gray, green, or blue infrastructure interventions—the latter two often combined as “nature-based solutions.” Nonstructural interventions include changes to building codes or improvements to warning systems and response capability or strengthening and aligning the institutional setup of flood risk management across agencies.

Structural interventions are often costlier and thus may require significant capital investments and may take many years to implement within an urban environment where space is limited, and social safeguards may take time to fulfill. Therefore, having an idea of the budget, the time necessary for implementing the intervention, and the types of interventions applicable to the given situation at the beginning of a project can be useful.

Figure 1.5 Types of Structural Interventions for Urban Flood Risk Management



Note: For more details about gray, blue, and green infrastructural interventions, see the glossary.

1.7

APPROACHES—FROM DETERMINISTIC TO PROBABILISTIC

Deterministic modeling. The investigation of flooding in a city or region is often initiated by a particularly damaging event, and where the data allow, it is common to attempt to replicate this event using suitable numerical modeling techniques. This can be a useful exercise to understand that particular event, but it can also help improve understanding of the flood dynamics or issues in the study area. The results of this model can be used for future broader model calibration or verification. When placed in the context of other historical events, it can also provide a starting point for understanding the future likelihood (or probability) of extreme events. This type of single-event modeling can be referred to as "deterministic" modeling because each event has a single set of inputs, which leads to a specific outcome.

Semi-probabilistic modeling. Where flood hazard or risk is being assessed, it is insufficient to base the analysis on a single event. Both hazard and risk must include an element of the likelihood (or probability) of occurrence across a range of possible events. For a flood hazard assessment, this means typically that the analysis must include several flood events of varied severity and with a defined probability of occurring (more than three but usually around five or six return periods). This will provide the range of severity and probability of flooding in bands (associated with the event return period) at any given location across the study area. For a flood risk assessment, this event probability is also used as the probability of an estimated amount of damage or other impact occurring and is combined with the impacts of other more or less frequent events to provide a fuller picture of the potential impacts.

This approach to modeling is often referred to as "semi-probabilistic." Each discrete event is synthetic and, in one sense, is deterministic because it is derived from a single set of inputs, resulting in a single outcome. However, in reality, it does not represent a specific flood event but rather the theoretical outcome of a statistical event of a given likelihood (or probability).

Probabilistic modeling. This semi-probabilistic approach tends to be the most common method of carrying out a hazard or risk assessment because it can be relatively quick and simple to implement, and it is relatively easy to understand and use the results. More recently, however, a fuller probabilistic approach is being promoted that, instead of using a single statistical event (derived to represent a single probability), attempts to replicate the real world and uses a synthetic set of climate (or coastal) events. This event set usually will contain a vast number of possible scenarios, typically 10,000 or more—including occasional occurrences of the most extreme probable events down to multiple incidences of the more frequent low-impact events. It will also include different joint probabilities of all the main sources of flooding as well as different flood mechanisms (for example, high tides coupled with heavy rain) that may result in the same frequency of event but with a different distribution or extent of flooding. This "probabilistic" approach to both flood hazard and flood risk can be computationally heavy, but with improvements in computer power and better global datasets that can drive this type of analysis, it is becoming the preferred approach under some conditions.

Notably, the terms describing these approaches to modeling—deterministic, semi-probabilistic, and probabilistic—can be used in different ways and may mean different things to some firms or individuals. For example, some practitioners might refer to a semi-probabilistic analysis as either a "deterministic" assessment or a "probabilistic" assessment. It is, therefore, important at the start to be very clear about what is required so there is no misunderstanding.

Complex scenarios such as barrage operations; blockages; or joint probability of different flood sources, different antecedent conditions, different storm durations, variable distribution of localized storms, and so on, can all be considered in a more realistic and representative way using this approach. A fully probabilistic approach should be considered more seriously as these methods become more established.

The methods described above relate to developing flood hazard data. Either of these semi-probabilistic or fully probabilistic methods can further define risk and will be carried out in essentially the same way regardless of the hazard data. However, the process of developing a probabilistic risk assessment first requires a probabilistic hazard dataset: instead of applying the flood data for each individual return period event to the exposure data, and calculating the impact in bands, the fully probabilistic approach applies an effectively infinite range of probability and depths of flooding across the entire study area. A probabilistic risk assessment can therefore give a more representative distribution of risk metrics across the study area than the banded approach associated with the semi-probabilistic approach. In addition, the probabilistic approach can be used for remodeling the flood hazard with the intervention built into the hydrological or hydraulic modeling process.

A different set of flood depth and probability maps will be generated that can then be applied to the same risk model to determine in detail how the intervention is likely to change the overall risk.

Because the semi-probabilistic approach tends to be more common for Level 2 studies, the handbook will mainly focus on the semi-probabilistic approach, using discrete extreme events at different return periods (probabilities) to deal with the extreme events. In chapter 2, the handbook elaborates more fully on how a full probabilistic assessment may be carried out as necessary.

1.8 EXISTING DATA AND MODELS

Studies may already have been carried out to assess flood issues in a certain urban environment. These studies often contain valuable insights and information, which can be useful for the ongoing assignment. In addition to this, data may have been collected and models developed as part of previous assignments or other programs, which could be used as a starting point. Open-source and global datasets can also be used to complement previous datasets. Identification of all potential data sources, models, and reports is essential to make optimal use of the existing knowledge and data.

Relevant questions related to data and documents for urban flood risk assessments include the following:

What topography data are available?

Such data include, for instance, global digital terrain models (DTMs)—such as Shuttle Radar Topography Mission (SRTM) and Multi-Error-Removed Improved-Terrain (MERIT)—and locally available data such as laser imaging, detection, and ranging (LiDAR); high-resolution satellite or orthophoto imagery; drone survey data; and bathymetric surveys of water bodies.

Is there any existing flood protection infrastructure, and what is the state of maintenance or conveyance and protection level?

Infrastructure documentation includes, for instance, the layout and dimensions of primary and secondary drainage infrastructure such as road drainage, canals, culverts, pump stations, and tidal gates, as well as the dimensions and characteristics of coastal or fluvial embankments, dunes, seawalls, mangroves, and so on.

Are any existing flood, exposure, or vulnerability data available?

Seek, for instance, data on global or local flood hazard maps, known and mapped flood hot spots, OpenStreetMap data, cadastre system data, building types and replacements costs, population distribution and characteristics (age, gender, income, and so on), and historic losses during flood events.

What hydrometeorological data are available?

These data include, for instance, global datasets—such as Multi-Source Weighted-Ensemble Precipitation (MSWEP) or European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5)—but also local datasets with time series of rainfall and winds, water levels, or river discharges depending on relevant hazard types from hydrometeorological institutes or other relevant agencies or authorities (such as ports or airports).

Are there any existing numerical models for flood hazard modeling?

If so, when were these done, by whom, by what method, and how accurate are they? For instance, could existing hydrological, hydraulic, and risk models be reused, could some component data be extracted, and are the models available under data sharing arrangements?

What master plans and design studies have been developed, and to what extent have they been implemented?

Often, they provide useful information and data for existing infrastructure such as drainage networks and hot spots of areas at risk based on historical knowledge or previous modeling.

The availability and accuracy of the existing data or models can influence the approach and determine the accuracy achievable within the Level 2 analysis and may significantly affect the time and budget required.

Data and document management are essential throughout an urban flood risk assessment. Data should be in a uniform coordinate system and uniform reference level. Collected data but also generated data during the project must be stored properly to ensure that these data are available for later use and can also be transferred to relevant local agencies. The data should be accompanied with sufficient metadata describing the origin, entities, and values of the data under consideration. Online users can be of great help to exchange and review newly generated datasets between the various parties involved in such an assignment.

1.9 INSTITUTIONAL SETTING

Before the start of an urban flood risk assessment (or at least very early in the process), an analysis of the stakeholders and institutional setting should be carried out to understand who is best placed to take ownership, who can provide support, and who are the data and knowledge holders. Tailoring solutions based on the stakeholder and institutional setting is essential for the long-term success of interventions.

Relevant questions in this regard include the following:

?

What are government bodies' or institutions' responsibilities or involvement in flood reduction, adaptation, or management—prevention, planning, and emergency response?

?

What legislation or policies are relevant for flood management—taxes, protection levels, land ownership, setbacks, planning, and building permits?

?

What funding streams exist for the operation, maintenance, and investments in flood management?

?

What is the existing role and knowledge of communities in flood management—flooding warning systems, emergency plans, and evacuation routes?

?

Who holds critical data for flood hazard and risk analysis, such as rainfall, water levels, existing drainage infrastructure, recorded damages, and exposure?

An initial analysis of these aspects should be done during the preparation for the urban flood risk assessment. Especially the role of the institutional setup in flood risk management is critical to analyze in parallel with the more technical analysis because a convoluted setup with overlapping mandates and with many agencies involved can be a source of (increasing) flood risk by itself. These aspects can be further detailed during the study and also taken into consideration when interventions are identified and prioritized.

It is advisable to set up a working group with relevant beneficiaries to support the urban flood risk assessment. Members of the working group could have a mandate for managing floods, implementing works, holding relevant data, using or paying for the services of the flood risk management or drainage system, or any combination of these. Relevant stakeholders often include hydrometeorological agencies, public works departments, disaster risk management entities, environmental and urban planning authorities, and local communities. A working group's tasks may include reviewing the terms of reference, delivering relevant data and documents for the assessment, providing access to sites and support to field trips, gathering relevant other stakeholders for working sessions, and providing recommendations for the deliverables.

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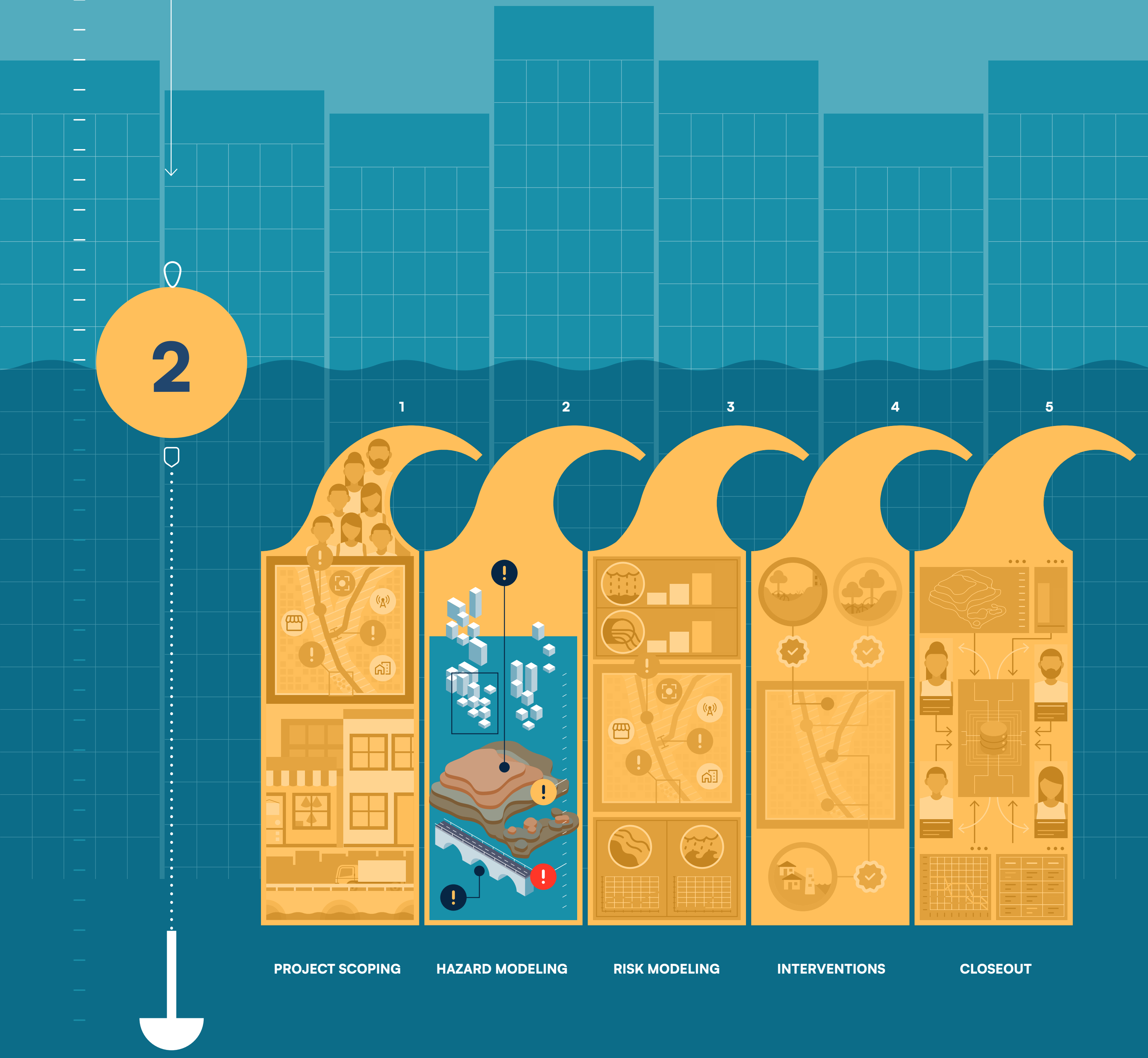
ENDNOTES

1 The inception phase of the project is a key phase of a project. This is when the consultant begins to get familiar with the assignment, pulls the data together, and meets the stakeholders. The Inception Report is a key milestone as it refines and confirms the approach, level of detail, accuracy, timing, deliverables, risks associated with the project; maps the stakeholders; and generally states how the project will proceed. The end of this stage is normally marked by a formal agreement from the client before proceeding to the actual assessment part of the assignment.

2 Gray, green, and blue interventions refer to climate change adaptation or mitigation through "gray" infrastructures (hard or engineering approaches) or through "green" and "blue" approaches encompassing biophysical systems, ecosystems, and their services. For more detail, see the respective definitions in the glossary.

CHAPTER

FLOOD HAZARD ASSESSMENT



2.1

INITIAL CONSIDERATIONS

Flood hazard assessments capture and quantify the flood characteristics—extent, depth, speed—in a particular location and attribute a likely frequency of occurrence to a given severity of flooding. To achieve this, some initial considerations and questions are necessary:

1

The first consideration is whether a numerical modeling analysis is actually required. The most probable answer is "Yes." However, situations may arise where sufficient records over a sufficiently long period of time may provide all the answers needed, at least for a preliminary Level 1 assessment.

2

If the answer to the above question is "Yes," what will be the most appropriate modeling approach to use? For flood hazard modeling, two aspects of flooding are typically analyzed or modeled separately: (1) how much water is there (the hydrology); and (2) where does the water go (the hydraulics).

3

When considering hydrology, it is important to understand the source of the floodwater. It can be directly from rainfall (usually referred to as pluvial flooding); from rivers exceeding their capacity (fluvial flooding); from the sea (coastal flooding—that is, elevated tidal levels during storms); or, more likely, a combination of these. The source of the flooding determines what type of boundary conditions for the modeling must be prescribed.

4

When considering hydraulics, the approach is often a compromise between the level of accuracy possible and the time, money, and data available to carry out the work. The approach selected must meet the minimum required resolution and quality required for the problem at hand and the project stage. Hydraulic modeling can typically be categorized dimensionally—as 0D, 1D, 2D, 1D-2D, or 3D—and can be run as a steady state or unsteady state model, depending on the dynamics of the flooding problem being analyzed. Figure 2.1 serves as an aid to selecting the appropriate model.

5

Which digital terrain model (DTM) is necessary for the assessment? What horizontal resolution and vertical accuracy is required? How can the vertical reference level of the DTM be tied to other relevant levels (for example, mean sea levels and embankment and invert levels) to ensure consistency? What is the role of subsidence (whether natural or human-induced) on the ground elevations, and should the analysis account for this?

6

Which physical features are important in determining flow paths and areas of inundation such as man-made and natural waterways and drainage infrastructure (such as bridges, culverts, pumping stations, retention ponds, and flood defense embankments), and what kind of gray infrastructure or nature-based interventions are considered? And should they be included during hazard assessment, option analysis, or both?

7

Does the assessment need to be deterministic or probabilistic? What benefits would each bring? Related to this, which flood simulations and scenarios should be carried out: a set of different events at different return periods or a sufficiently long synthetic time series? How will the model results be calibrated or validated against reality?

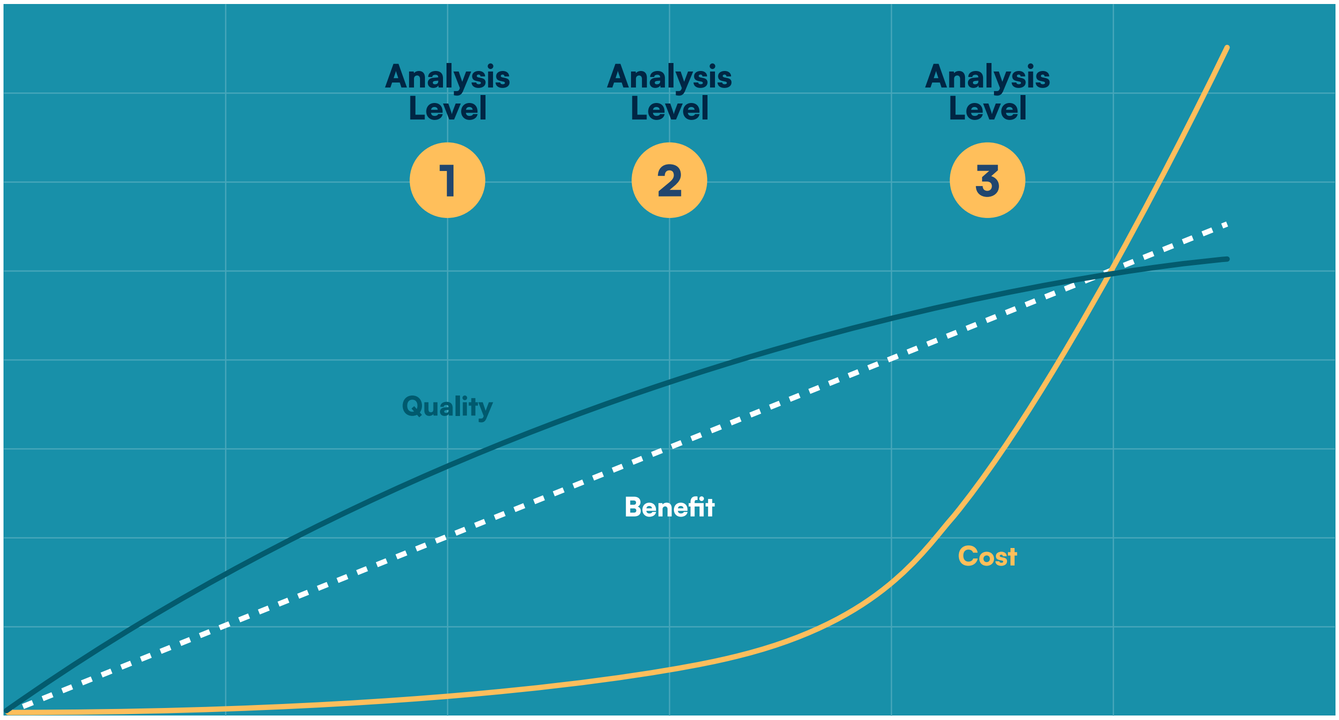
Hydrological and hydraulic modeling in an urban setting is not an exact science; adequate or sufficient skills and judgment will always be required to select the detail and resolution required and the best overall method. The aim is to balance the cost and time of doing the study with the resulting accuracy and confidence required. Figure 2.1 demonstrates this relationship between effort or cost, quality of the outputs, and the benefits realized through carrying out the study. The benefits link directly to the requirements of the study; therefore, the idea is to select the level of benefit that matches the optimum cost and quality.

Costs and time can escalate exponentially by attempting to achieve high accuracy and by including details that will not significantly alter the analysis outcome.
It is important to remember the 80-20 rule: It is normally possible to produce acceptable strategic (Level 2) results (that is, 80 percent of what might be possible)

for comparatively little cost. The remaining 20 percent, which often may not be needed, is where the escalating costs can lie.

Flood modeling consists of a chain of processes and relies on a range of data types and sources, whereby the overall quality and benefits from the modeling results are dependent on the weakest link in that chain. Ensuring that all aspects of the process are optimal will help ensure that the modeling meets the requirements of the analysis.

Figure 2.1 **Trade-Offs in Flood Hazard Modeling, by Analysis Level**



Note: Figure illustrates the relationship between the strategic level of hydrological or hydraulic modeling and (a) the cost (including time and effort), (b) the quality of outputs, and (c) the benefits required from the study. Level 1 analysis refers to preliminary analysis; Level 2 to strategic analysis; and Level 3 to detailed, high-resolution analysis (as further discussed in the Overview and chapter 1).

2.2 HYDROLOGICAL ANALYSIS

The hydrological analysis required for a Level 2 flood modeling exercise considers mainly the inputs to the hydraulic modeling process. A key first step in setting up the analysis is to understand the main drivers of flooding for a specific urban context and the possibility of joint occurrence of these drivers. Typical drivers of flooding in a coastal city are local rainfall, high river water levels, and elevated sea levels due to tides in combination with (extra-)tropical wind events. These drivers are not static but may increase over time because of climate change and other anthropogenic changes (for example, reservoirs or upstream deforestation). It is critical to understand the drivers and their potential joint occurrence at an early stage to focus the hydrological analysis.

Flood hazard and risk modeling requires the consideration of a range of flood events of increasing severity, which normally involves simulating storms or events of different return period events (or frequencies). These typically may range, for example, from relatively frequent events (at 2-year return periods) that would happen every year or so, up to events that would be far more severe but relatively unlikely to occur (at 100-year return periods). This analysis—to determine the scale and frequency of flood events in a given area—is a key to understanding the flood risk, and the outputs of the frequency analysis will be flows, storm surge, or rainfall events for a range of severity that will be used to drive the hydraulic modeling.

The importance of the hydrological part of the analysis should not be underestimated. It is heavily data dependent (particularly on long records) and may employ a range of statistical techniques to deal with uncertainty; joint probability (for example, the chance of different sources of flooding occurring at the same time); and the effect of spatial variability and scale. The outputs are usually a set of time series of event data that will be used as boundary conditions for the hydraulic modeling.

Calibration of the hydrological models requires the use of measured data captured from one or more flood events that can be used to drive the models being developed for the study area. This helps define the parameters within the model that best represent the processes (either physically or numerically) and can be based on simple statistical “goodness of fit” measures. This process will also aid a better understanding of the physical processes during the event, which may not have been recorded.

2.2.1 Types of Boundary Conditions and Joint Probability

Five types of model boundary conditions are typically applied within a flood model: (1) rainfall, (2) infiltration, (3) flow, (4) water levels and waves, and (5) pumps and flow control structures. Whether only a few or all are relevant and must be analyzed and defined in detail very much depends on the specific urban setting. Without being exhaustive, the subsections below describe the details of setting these boundary conditions as well as the various possible combinations that may occur. Table 2.1 provides some examples of cities that have been subject to these various conditions. Assessment of readily available data, studies, and local expert knowledge are essential to quickly identify which of these boundary conditions are critical for flood hazard and risk mapping purposes.

Table 2.1 Flood Model Boundary Conditions Affecting Selected Cities

CITY EXAMPLES	LOCAL RAINFALL	RIVER FLOW	TIDE	STORM SURGE AND/OR WAVES
Kinshasa (Congo, Dem. Rep.), Bamako (Mali)	✓	✓	—	—
Banjul (The Gambia), Monrovia (Liberia), Paramaribo (Suriname)[a]	✓	—	✓	—
Hai Phong (Vietnam), Khulna (Bangladesh)	✓	✓	✓	✓
Beira (Mozambique), Cox's Bazar (Bangladesh)	✓	—	✓	✓

Note: These cities face some small elevated tidal levels due to wind, but this effect of storm surge is generally very small (less than 10 centimeters) because of the very mild wind climate in these regions.

Because multiple flood hazard mechanisms can play roles within a specific urban setting, the joint probability of these mechanisms is therefore crucial to understand at an early stage of a Level 2 assessment. The joint probability will determine how the boundary conditions must be defined to evaluate realistic urban flood scenarios for extreme events. If a city is threatened by local rainfall and storm surge by cyclones (as occurred in Beira, Mozambique), then the question becomes which combinations of rainfall and storm surge should be selected for flood mapping.

A local rainfall event with a 100-year return period in combination with a 100-year storm surge event can be a realistic scenario for estimating the 100-year flood situation if the storm surge and rainfall would be fully correlated. But if these two processes are completely uncorrelated, then this scenario of 100-year rainfall and 100-year storm surge has a return period of 10,000 years. In that case, a 100-year storm surge situation and a 1-year local rainfall event (and vice versa) are realistic scenarios. This example highlights the importance of calculating the joint probability of different hazard mechanisms to achieve realistic flood mapping of urban environments.

2.2.1.1 Rainfall

Rainfall data are almost always among the main input requirements for citywide (Level 2) flood modeling. These data can usually be applied as a direct input to each cell of the 2D model grid (a common approach for pluvial flooding), often referred to as the “rain-on-grid” approach. Rainfall data can also be applied to a separate rainfall runoff (hydrological) model for the upstream basin to derive inflows (hydrographs) to drive the hydraulic model (a common approach where rivers are the main source of flooding).

Whether the modeling exercise aims to replicate a specific event or to develop representative “design storms” with particular statistical properties (that is, a specific return period), the rainfall data’s accuracy is important. In addition to the total ***amount*** of rainfall, major factors in a given flood event include the ***spatial distribution*** of rainfall within a basin and the ***changes in intensity*** throughout the period. The following factors are important to consider regarding rainfall data:

- Local historical rainfall records, if of reasonable quality, can prove extremely valuable, and even short records (spanning only one or two rainy seasons) can provide useful calibration and verification data.
- Remote-sensing rainfall data (MSWEP, TRMM, GPM, ERA5, and CHIRPS) can be used if local data are limited in coverage, duration, or quality.[1]

- Urban flood modeling requires short-duration (subdaily) rainfall inputs, which normally require automatic gauges (for example, tipping bucket, gravimetric, drip, count, and so on). The widespread use of these types of rain gauges is a relatively recent development in hydrometry, and so the length of record may extend only a few decades. Notwithstanding, the value of even these short periods of record should not be underestimated as this will inform the selection of design storm duration and intensity, which can be very significant in urban flood generation.
- Most meteorological services only provide daily values (mostly from manual gauges), which provide part of the overall rainfall characteristics. However, the distribution and intensity within a single day are essential.
- It is often necessary to use data from a range of sources to achieve the best practical outcome.
- Intensity-duration-frequency (IDF) curves, which are often a key output from the previously mentioned frequency analysis, can be produced through a number of techniques; the use of local data is the preferred method. Where local data are not available, regional curves can be used and adjusted to fit the local recorded daily or, more preferably, subdaily data.

Local rainfall data records often cover short periods and often contain inconsistencies. Global data can be used as an alternative but are also far from perfect. A robust assessment of the data accuracy (both locally and globally derived) and uncertainties is key for good flood hazard mapping results. Several simple checks may include (1) comparative double-mass curves for rain gauges in the area of interest to highlight discrepancies or interruption of the record; and (2) an outlier assessment before extreme value analysis, where an outlier (either outside the expected range for the year or the season) would erroneously skew the extreme value analysis and therefore the hazard modeling results.

2.2.1.2 Infiltration

Along with rainfall data, infiltration is an important factor to consider in the urban flood modeling process. It is a natural process that depends on the land cover and soil characteristics within the study area. Even within a completely natural basin, the amount of infiltration that can occur will significantly influence the amount of runoff generated from a given storm. It will also affect the amount of rainfall that soaks into the ground providing recharge for groundwater resources, which in turn will influence the baseflow within the surface-water streams and rivers.

In an urban environment, infiltration is even more critical to the way the catchment behaves and responds to rainfall. Heavily compacted soils or extensive areas of impermeable material (such as building roofs or paved areas) will reduce the water soaking into the ground and therefore increase the water running off into the drainage system. Conversely, increasing infiltration volume and rates can delay and reduce peak flows entering the urban drainage system.

The effect infiltration can have on runoff is variable and complex, and it depends on the type of storm (its intensity and duration) as well as the antecedent conditions (how saturated the soil already is at the start of a storm). For simplicity, it is sometimes assumed that infiltration is minimal over a heavily built-up area and therefore neglected in the modeling. However, substantial parts of cities generally still have permeable soils, and there is a growing interest in applying green infrastructure to enhance the infiltration—such as through more permeable pavements and the introduction of urban forests or swales. Inclusion of infiltration in urban flood modeling is therefore essential because it is not only an important part of the hydrological process but also can be used as one of the possible intervention strategies to mitigate urban floods (see, for example, Bai et al. 2018).

Infiltration depends on many variables, and it is generally recommended that it be included either explicitly or implicitly in the urban flood hazard modeling process. Many of the current hydraulic models, when applying rainfall directly to the model (that is, rain-on-grid methods), can explicitly include infiltration within the modeled process by including an infiltration loss in each 2D grid cell. The infiltration rate for each grid cell can be made time- and space-dependent to account for variations in soil conditions. When rainfall is modeled as an inflow (that is, converted to a flow hydrograph), infiltration tends to be simply subtracted from the rainfall as part of the hydrological process, either as a distributed variable or simply applied as a lumped (or averaged) value.

When infiltration is explicitly taken into account in the modeling process, the infiltration capacity of the soil must be set. Estimates of infiltration capacity must often be based on literature values because local data are often not available. Typical infiltration rates for soils vary from 30 millimeters per hour for sandy soils to less than 5 millimeters per hour for clayey soils. Notably, these values have a large uncertainty because of the complexity and variability of the infiltration process (for example, dependency on the existing water content, exact soil structure, depth and texture, and so on). This uncertainty must be recognized when infiltration is included within the flood modeling process. For further reading on rainfall infiltration in urban environments and modeling thereof, refer to Zeleňáková, Hudáková, and Stec (2020).

2.2.1.3 Runoff

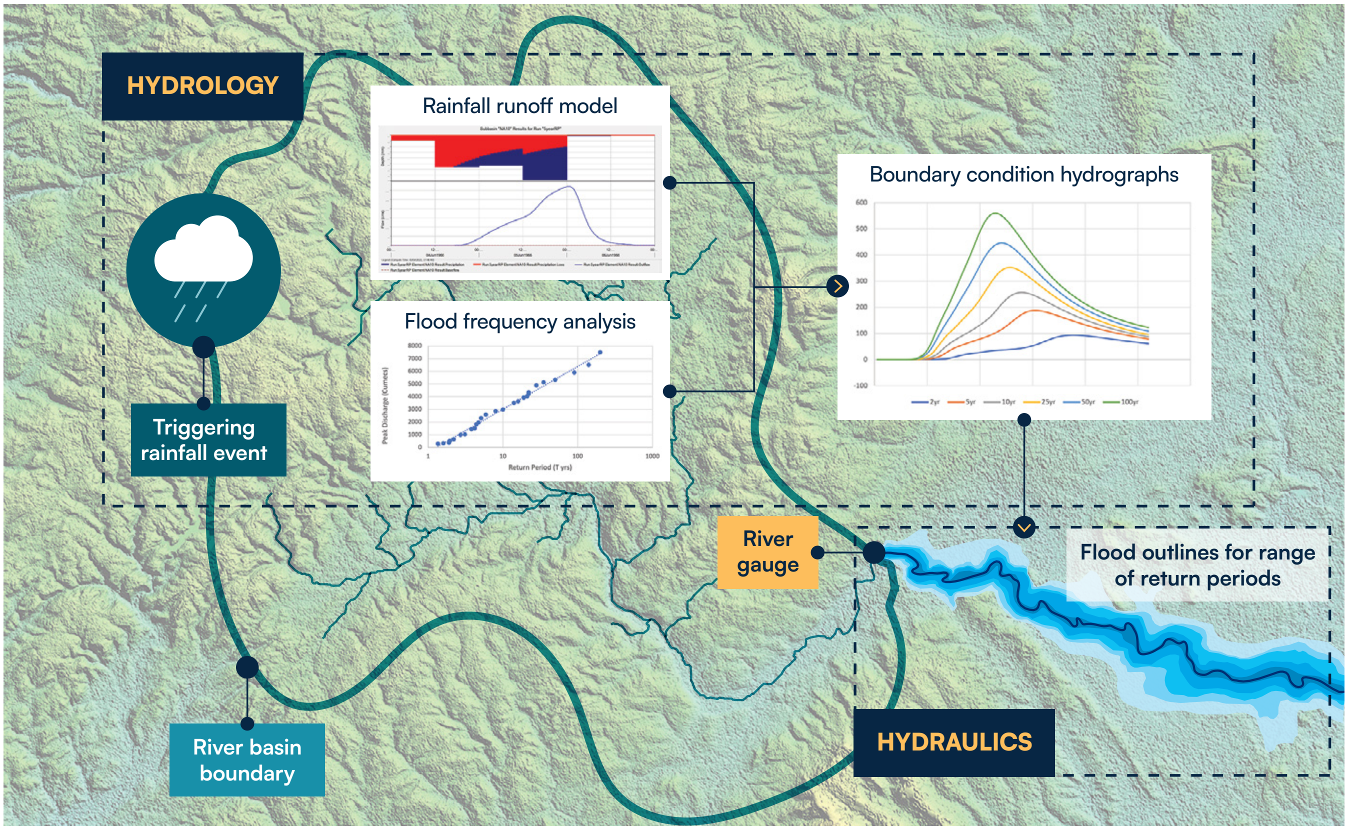
Design flow data are usually applied to a river channel or canal either as a boundary condition to a 1D channel or directly onto a 2D surface within a river or canal. Flow data are normally applied as a hydrograph (that is, changing flow against time) at the upstream boundary of the model, although they can be added at key locations within a model—for instance, at a discharge point of a controlled system or the exit point of a culvert.

A design storm's stream flow is ideally estimated using extreme value frequency analysis methods based on a long and reliable stream flow record collected at a formally recognized flow gauging station. Statistical methods are used to extrapolate measured or, if unavailable, modeled data (for example, using annual maxima to generate extreme events). Where stream gauging provides a sufficient length of flow records (20 years or more), statistical analysis can be carried out on the gauged data. Where gauge records are short but rainfall data are more readily available, the recorded flows can be used to calibrate a rainfall runoff model to extend the flow records for statistical analysis.

A wide range of rainfall runoff modeling approaches could be applied to urban drainage systems, varying in complexity and applicability. They include simple conceptual models (rational method); empirical models (curve number methods or the Sacramento Model); physically based models (for example, the MIKE System Hydrologique European [SHE] or Shanbei model [SBM]); and lumped versus grid-distributed model approaches. The selection of the modeling approach and software will largely be driven by the drainage system characteristics, the available data, the required resolution and coverage of outputs, and often the preference of the firm carrying out the work.

Where no gauge records exist for the basin, a combination of rainfall runoff modeling can be applied with donor catchment or regional data. Estimating the rainfall runoff model parameters for ungauged catchments with information from gauged catchments is generally referred to as "regionalization" (see, for example, Meigh, Farquharson, and Sutcliffe 1997), and widely used concepts are based either on spatial proximity or similar catchment attributes. The statistical approach (for example, choice of the distribution type and the fitting procedure) to determine these relationships with the ungauged catchment can significantly affect the end result. Because the data records are often short, data extrapolation of short time series results in significant uncertainties for estimates of extreme events (figure 2.2).

Figure 2.2 Typical Statistical Analysis Approach



Caution should always be applied when dealing with extreme river runoff events because they are rare, usually difficult to measure, and often inferred from either extrapolated rating curves or from uncertain measurements. The analysis should not rely on statistical measures alone and must include an element of professional judgment and common sense. Also, the joint occurrence of extreme river discharges and downstream water levels (for example, due to storm surge) may make the derivation of extreme discharge boundary conditions less straightforward, as further discussed in the next subsection.

2.2.1.4 Water Levels and Waves

Water levels and waves are often applied at the downstream end of a hydraulic model to represent a large waterbody (for example, the sea, a lake, or even a large river that may not be included directly within the model) to allow water to exit or enter the model according to the downstream conditions. Setting correct conditions may be relatively straightforward for a city located at a nontidal river. However, it can be quite difficult in a coastal city context with a river entering the sea where there is also the possibility of storm surge and waves. In this case, the joint occurrence of the various drivers such as river discharge, storm surge, and incoming high waves must be carefully considered.

In a (nontidal) river situation, a water level is generally imposed at the downstream end of a river section. It is important that the downstream boundary (for example, normal depth) be at least a backwater length away from the place of interest so results (for example, scheme design) are not strongly influenced by the boundary conditions. The boundary condition in this situation can be set up in various ways but most commonly as (1) a stage hydrograph that can be constant or may vary over time depending on the river flow input; or (2) a simple Manning's equation referred to as a "normal depth" relationship that typically depends on the surface-water slope at that location and controls the amount of water as it leaves (or in some cases enters) the downstream end of the model.

Deriving boundary conditions in a coastal setting is often much more complicated. In these environments, different coastal processes (such as tides, waves, storm surge, or even tsunamis) may result in, or have a significant impact on, flooding. In such environments, a broad site-specific understanding of the governing coastal processes is important. Specific attention shall be paid to the joint occurrence of these processes, which is essential for setting good boundary conditions for flood modeling. For example, storm surge due to tropical storms (hurricanes, cyclones, or typhoons) and tidal water levels are independent. Another example is a large swell event and high tidal water levels. On the other hand, storm surge and high wind-generated waves are generally closely dependent because these are generated by the same storm event. In deriving flood hazard scenarios with different return periods, these dependencies must be carefully considered.

Coastal boundary conditions for water levels and waves for urban flood modeling can be set up in several ways, most commonly (1) a stage hydrograph that allows water to enter or leave the model, which may vary over time (such as if a storm surge is superimposed on a tidal hydrograph); and (2) a discharge hydrograph that enters a set amount of water into the modeling domain (for instance, because of wave overtopping from the sea).

Deriving appropriate coastal boundary conditions for these stage or discharge hydrographs can be done in various ways by (combinations of) collecting and analyzing local measurements or using numerical modeling from global or tailored dynamic hydrometeorological models, depending on the specific coastal processes and local data viability at hand. Where there is a lot of uncertainty in these processes—and in particular, their combined influences—it is good practice to carry out a sensitivity analysis over a range of combinations. It is also common to use the worst (likely) case scenario to ensure that a conservative approach is taken when looking at any mitigation options.

When specific data are concerned, the following may be considered.

Tidal water levels. Local monitoring is usually the best source but needs to be tied into a recognized datum—for example, a time series that picks up full cycle maximum and minimum levels for a minimum of two years. Measurements and tidal predictions are generally given referenced to mean sea level (MSL) or chart datum, which are rarely exactly related to the local datum (the DTM), so additional effort will be required to find this relationship.

Local tide astronomic tide tables are available for most cities and ports around the globe. These can be used with time series data and combined with storm surge estimates through empirical methods such as the World Meteorological Organization's "Guide to Storm Surge Forecasting" (WMO 2011).

A long-term water-level observational dataset is required if statistical analysis is required to derive extreme water levels for rare storm surge events as a result of tropical or extratropical weather systems. A time series of (at least) 10-20 years is often required to estimate storm surge levels up to a return period of 100 years with reasonable accuracy.

Global models such as the Global Tide and Storm Surge Model (GTSM) may provide tide and surge information if local data do not exist (Muis et al. 2016). These types of global models, however, do not capture intense local storms such as tropical weather systems for lack of resolution.

In regions prone to tropical storms, more advanced and detailed models are generally required to derive representative storm surge and wave scenarios and statistics when long-term data series are not available. Coastal boundary conditions of storm surge levels and waves can be generated by running a set of historical or synthetic storms derived from the statistics of the historical storms (such as track, intensity, pressure, and so on). For a recent overview, see Bakker et al. (2022) and the references therein.

River levels. Large rivers through or downstream from cities can be dealt with either as a fully dynamic part of the model, requiring bathymetry and flow inputs, or as a boundary condition where only the water level is applied at the point where the modeled drainage would enter (or be influenced by) the river. Normally only the latter is needed, but this requires some understanding of the river behavior and historical level records and often depends on the relationship with flow.

Local river-level observations and even discharge information is generally available if the river is sufficiently large. The quality of the time series data must be carefully checked for consistency and completeness. Also, changes over time that may affect water levels—such as sedimentation or erosion; upstream changes that affect river flows (deforestation reservoirs); or local interventions (for example, construction of embankments)—need careful attention before time series are used for estimating extreme events through statistical extrapolation.

Waves. Wave overtopping due to waves (wind, swell, or both) can cause considerable additional volumes of floodwater and an overtopping of a structure or defense and must be considered in exposed locations. Swell waves are characterized by their very regular long crests and long wave periods, whereas local wind waves are short-crested and have a more irregular pattern and short periods. A first-order practical guideline for identifying the distinction between nearshore swell and wind waves is a period of 10 seconds. If nearshore waves are relevant for a specific urban setting, a good understanding and thorough analysis of the governing wave processes for the situation is paramount.

Local nearshore wave observations for representative sea states are generally rare. Thus, long-term hindcast modeling is often necessary to translate offshore wave information to nearshore information for exposed locations. This requires information on incoming offshore swell and wind waves and/or local wind data, as well as detailed bathymetry to accurately represent important wave processes such as shoaling, refraction, and breaking.

Empirical methods are available for locations where wind waves are unlikely to be a significant issue (say, in estuaries or on sheltered coasts) based on wind fetch and depth. Simple 1D models such as SWAN 1D or XBeach can be used along straight open coasts, needing beach profiles, offshore swell/wind waves, and wind to estimate beach overtopping rates. If the bathymetry of the coast is more complex (for example, owing to the presence of islands or the foreshore bathymetry with bars and channels), 2D models are generally required to define accurate wave conditions near the coast. Also, these wave models must be applied in combination with tide or storm surge levels when temporal and spatial variations in nearshore water depth cannot be neglected.

2.2.1.5 Pumps and Gates

Flood defense or water-level management structures may already exist in flood-prone areas of cities and must be included within the analysis to ensure a full understanding of the flood dynamics. These structures may require simulation of discharge rates with a nonlinear response. This is normally achievable as a dynamic linked 1D element. The main features that are likely to require consideration as boundary conditions or flow control features are listed below.

Pumping

- Pumping rates for a pumping station normally relate to local water levels (either upstream-only or upstream-downstream relationship) up to a maximum installed capacity.
- The pumping station discharge rate is often limited to a stepwise control through switching multiple pumps on or off.
- Control rules are sometimes automated, normally documented, but occasionally recorded in personal memory. They need to be simplified and set up within the model.
- In some circumstances, implementation can be simplified by applying a predefined time-varying discharge hydrograph at the pump station location. This has some limitations for more detailed analysis but can be used to test the principle.

Flow Control Gates or Barrages

- Discharge rates from control gates normally relate to both upstream and downstream water levels and the type of structure (for example, tidal flaps). Thus, dynamic simulations are required.
- Gates and barrages may also have control rules that depend on other non-flood-related factors such as irrigation, hydropower, navigation, environmental considerations, and so on. It may be necessary to consider these factors as different scenarios that may alter the return period of the event.
- As with pumps, it may be possible to simplify the feature within the model to a time- or level-dependent discharge boundary condition that reflects the discharges to a large waterbody such as the sea.

2.3 HYDRAULIC ANALYSIS

2.3.1 Summary of Hydraulic Modeling Options

The hydraulic model is used to define and characterize the flood extent and depth as well as, if necessary, water velocity, duration, and speed of onset (and, in rare situations, could provide erosion, sediment load, and debris flow data). One of the main differences in modeling approaches relates to the number of dimensions the model resolves: 0D, 1D, 2D, or 3D (figure 2.3). They may use similar equations and methods internally but treat the whole problem of water movement very differently. These modeling approaches are feasible at different spatial scales and are defined below.

Figure 2.3 Decision Tree to Select Hydraulic Modeling Type for Flood Hazard Assessment

MODEL FEATURES	MODEL SELECTION
Best suited where a very quick and simple flood hazard or risk assessment is required—typically used for analysis of simple flood processes where the predominant factor in determining where inundation occurs is the water level at a known location. An example would be coastal flooding where the tide level determines the extent of inundation.	Is the flooding very simple, and can be adequately described in relation to a level or volume? YES: USE 0D MODELING / NO
Best suited to channel flow, flow within pipes or culverts, or flow within a well-defined flow path such as a narrow floodplain or valley floor. A simple model can be easily produced and will run very quickly with only a few surveyed cross sections at the point of interest, or it can be developed over a wide area with extensive channel survey, assuming that the channel is uniform between cross sections.	Is flooding associated with a channel or drain with a well-defined narrow flow route? YES: USE 1D MODELING / NO
Best suited to flooding of wide, flat, poorly defined areas where any in-channel flow is negligible in determining flood extent. This modeling approach is dependent on the quality of the digital terrain data available, but with sufficiently high resolution, it can accurately capture the river channels as well. It can be slow to run over large areas but is very simple and quick to set up.	Is flooding widely distributed across a floodplain or with poorly defined flow routes? YES: USE 2D MODELING / NO
Combining 1D and 2D modeling provides the best of both. It allows better distribution of flow across floodplains and particularly urban settings while capturing the detail of channels, drains, and other flow structures. It can be more complicated and time-consuming to set up and run, and it requires both an accurate DTM and local ground survey data.	Is flooding caused by a combination of ill-defined overland flow routes and well-defined channels? YES: USE 1D 2D MODELING / NO
Normally, 3D modeling is only required for the detailed design stage of a project and would be focused on a specific structure or feature (for example, a bridge, lock, sluice gates, and so on) that affects flow. The process requires a detailed survey of all relevant aspects of the problem; can be difficult, time-consuming, and costly to set up; and may require specialists' skills. It is therefore not normally recommended for flood hazard modeling.	Is the assessment for a detailed design around a complex structure or set of flow conditions? YES: USE 3D MODELING / NO

Note: DTM = digital terrain model; 1D = one-dimensional; 2D = two-dimensional; 0D = zero-dimensional.

Zero dimensions (0D). These simple (point or box) models look at volumes of water or relative water levels—for example, a geographic information system (GIS) approach to flood spreading according to sea level. This approach—although not, strictly speaking, hydraulic modeling—has a valuable place in quick analysis to provide preliminary or indicative results. The spatial scale of these models can be anything from a local assessment up to thousands of kilometers (regional to continental scale). Adequate GIS tools should be used to make sure that no floods are predicted in terrain depressions that are not connected to the source and to ensure the model also considers the duration of the flood event and the likely flood volume. For example, if a storm event lasts only a few hours, it may produce less water than needed to flood the entire flood-prone area.

One dimension (1D). These numerical models calculate fluid movement in a single dimension, normally within a channel or conduit, where the single dimension is along the direction of the channel or conduit. The typical spatial scale of these models can be very localized for engineering design up to hundreds of square kilometers (urban to regional scale). The urban topography is captured through storage nodes and channels in these types of models, relying on georeferenced, surveyed channel and floodplain cross sections as a primary input.

Two dimensions (2D). These numerical models calculate fluid movement in two dimensions, typically across a floodplain or land surface, where the two dimensions of movement occur in any direction on the horizontal plane. The typical scale of these models tends to be from tens of square kilometers up to several hundred square kilometers (urban district to urban scale). These models use a two-dimensional DTM as an important input, from which it creates a grid of computation cells that use the ground level in each cell, and the relative ground levels in surrounding cells, to determine the direction and velocity of water movement across the land surface.

One and two dimensions (1D-2D): These numerical models combine the 1D and 2D approaches for the modeling domain. Channels and structures are generally schematized as a 1D model, in which the flow direction is clearly in a single dimension. Floodplains or urban areas where the flow direction is less obvious are schematized in two dimensions.

In a 1D-2D approach, the 1D and 2D numerical models are coupled to ensure consistency of flows and water levels in the entire modeling domain. Hence, there is an exchange of flow between both models, and water can flow from the channel into the floodplain and vice versa during a time-dependent simulation. These models have the data and input requirements of both 1D and 2D models described above.

Three dimensions (3D): These complex numerical models capture fluid movement in all three dimensions. This can be achieved in one of two ways: (1) as a series of horizontal slices through the water depth, where each slice is treated as a 2D model, but certain parameters or values are passed between each slice to represent 3D physics; or (2) as a truly 3D computational fluid dynamics approach that solves sophisticated 3D equations, which can be used for very complex problems.

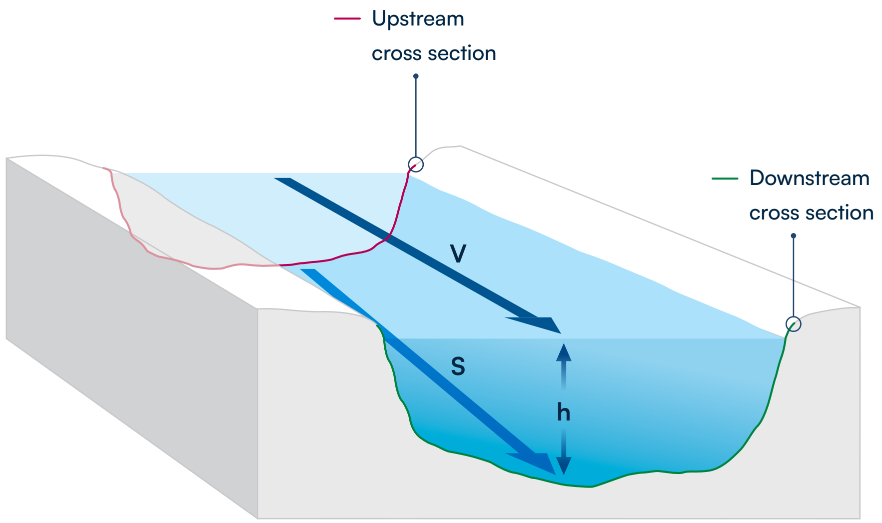
It is very unlikely that this approach will be needed in a Level 2 analysis; it is typically used for modeling complex local hydraulic situations and is focused on a specific structure or problem area. These models require a 3D digital representation of the structure, all relevant data such as bathymetry and topography, and potentially very large amounts of accurate detail.

Level 2 requirements: In general, a Level 2 analysis would require a 2D or a 1D-2D combined modeling approach. A 1D approach can be appropriate, where the data allow, for quick scans and sensitivity testing or scenario runs; when a large spatial scale must be covered; or as a starting point for more detailed 2D modeling in a Level 2 analysis. Three-dimensional modeling is generally not required or feasible for urban flood modeling at Level 2.

2.3.2 1D Flood Modeling

Hydraulic modeling in one dimension (1D) is the traditional approach to flood modeling and has been employed since before the advent of computers. The single dimension refers to flow along the channel, and the assumption is that the average flow along the channel can be estimated between two points—upstream and downstream—along the channel or flow conduit (which could be a pipe or culvert) using the St. Venant equations (figure 2.4). It assumes that the channel is uniform or gradually varying along its length and that flow is averaged in depth—that is, the variation of velocity along the channel with depth is averaged. This approach works well where water flow is largely contained within a channel or a well-defined topographic feature and where flow routes during flood events are well understood.

Figure 2.4 Model of the St. Venant Equations in Practice for 1D Hydraulic Modeling



V = (referred to as u in the equation below) the average water velocity between upstream and downstream cross sections

S = (in the equation below referred to as So) the average bed slope between the cross sections

A = Average cross section area of the water flow

h = Water depth

Q = Flow (usually in m³/s) between the upstream and downstream cross sections (Q = V x A)

S_f = (also from the equation below) Friction slope, which is a unitless factor which relates the rate of energy lost along a given length of channel, mainly due to friction.

ST. VENANT EQUATIONS - CONSERVATION OF MASS AND MOMENTUM

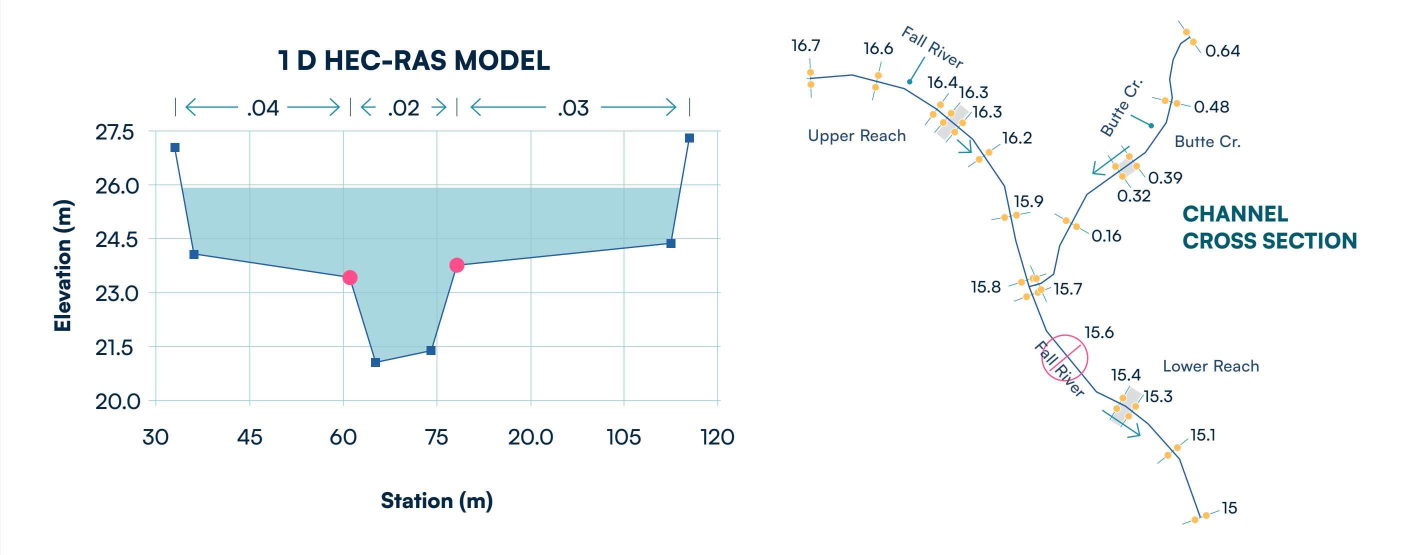
$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(uQ) + gA\left(\frac{\partial h}{\partial x} - S_0\right) + gAS_f = 0$$

One-dimensional modeling requires channel cross section data at sufficiently frequent intervals that accurately reflect the shape and size of the channel (figure 2.5). If out-of-bank flooding is to be simulated, cross sections will need to be extended to include the floodplain as well, but again, the floodplain must be well defined and relatively uniform (or at least gradually changing) between sections. Cross sections can be linked to form a large river or drainage network, and because the calculations can be carried out quickly, short model run times can be achieved with rapid production of results. The quality of the data used will determine the accuracy of the flood outputs, and the roughness is also an important parameter that should be included in the analysis.

The topography of an urban environment can be included as storage nodes in 1D models—usually as a depth-volume relationship with controlled inflow and outflow—to which rainfall can be added as a boundary condition. Such a storage node approach is almost never detailed enough for a flood risk assessment and therefore is mainly used for similar storage (flooding) upstream of the area of interest to ensure inflows are correct downstream. One-dimensional modeling also includes specific flow equations for structures such as weirs, culverts, bridges, pumps, and sluice gates, which are well established and ensure accurate and stable numerical computation of the flows and water levels.

Figure 2.5 **Example of HEC-RAS 1D Flood Model**



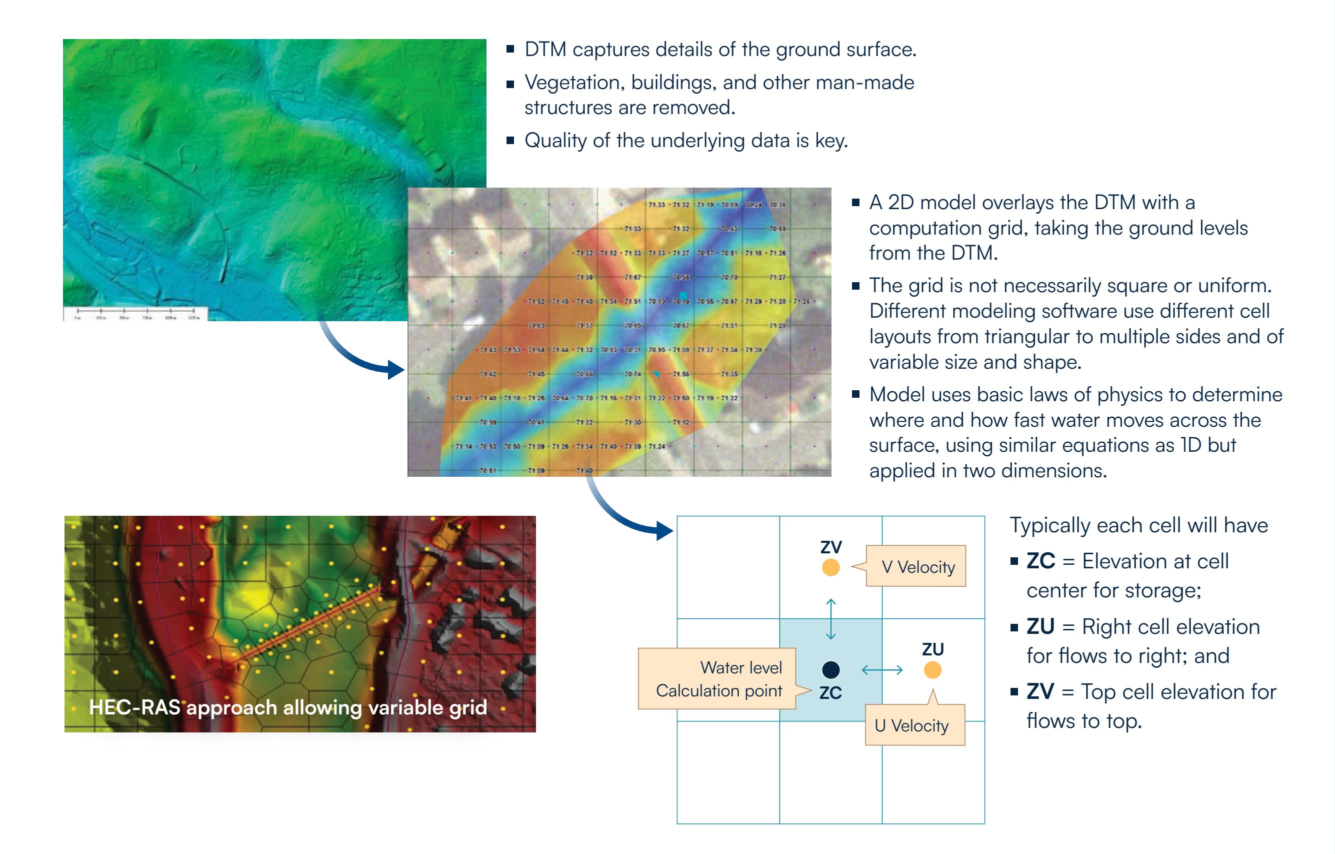
Source: Adapted from training material, US Army Corps of Engineers HEC-RAS.

Note: HEC = Hydrologic Engineering Center; m = meters; RAS = River Analysis System (of HEC).

2.3.3 2D Flood Modeling

A two-dimensional (2D) horizontal model, as the name implies, calculates water movement in all directions within a horizontal plane. It calculates the portion of the flow vector in both the "x" and "y" directions across the ground surface, resulting in an estimate of the overall flow in any direction. The modeling process overlays a representation of the ground surface in the form of a DTM onto a computation grid, which takes the ground elevation from the DTM. Figure 2.6 shows a typical arrangement. The DTM does not include features such as vegetation, parks, buildings, and other man-made structures and therefore represents what is termed the "bare earth." Where these features are important, they can be added back into the model in various ways using building footprint or urban forest and green parks polygons or roughness—often referred to as friction factors—as additional layers within the model. The quality of these underlying data is key to determining the accuracy of the modeled flood outputs.

Figure 2.6 Typical 2D Flood Modeling



Note: DTM = digital terrain model; HEC = Hydrologic Engineering Center; RAS = River Analysis System; 1D = one-dimensional; 2D = two-dimensional.

In many modern modeling software packages, the computational grid of 2D models is not necessarily always square or uniform. This can allow for smaller cells that more accurately capture the underlying topography or cells that align better with the movement of the water in areas where this may be important. Different modeling software uses different cell layouts, from triangular to multiple sides and in variable sizes and shapes. The model uses basic laws of physics to determine where and how fast water moves across the surface, using similar equations as 1D models but applied in two perpendicular dimensions.

Recent developments in modeling software allow high-resolution subgrids within each computation cell that can significantly improve performance. This feature enables the overall flow calculation to be run on a large grid cell, but each individual cell can have a precalculated depth-volume relationship based on the detailed topography within the cell, and a precalculated depth-discharge relationship along the cell boundary, again based on the detailed topography along the boundary that more accurately reflects the flows between each cell of the model.

2.3.4 Comparing 1D and 2D Modeling Approaches

Figure 2.7 compares the ways in which a 1D model and a 5-meter-resolution 2D model might represent a 20-meter-wide channel. The 1D model (green line) is constructed from surveyed cross sections, and the 2D model (orange line) is constructed with 5-meter-resolution cells (indicated by short red horizontal lines). At 5 meters' resolution, the 2D model captures the shape of the channel reasonably well. However, most remote sensing processes do not see through water, so the depth of the channel is often underestimated and may need additional processing or field data collection.

Figure 2.7 **Comparison of 1D and 2D Models in Capturing Flow Area of a 20-Meter-Wide Channel at 5-Meter Resolution**

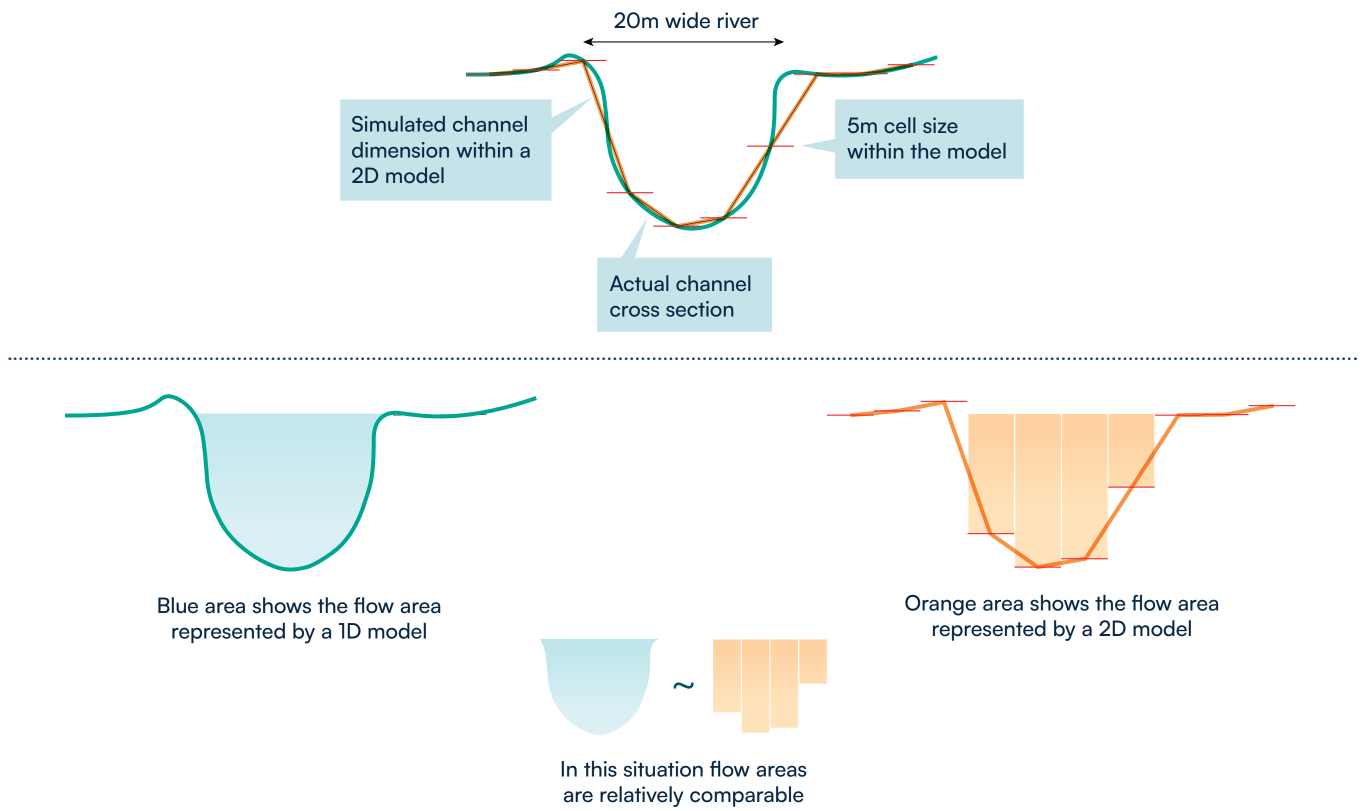


Figure 2.8 compares how a 1D model and a 30-meter-resolution 2D model might represent the same 20-meter-wide channel. Again, the 1D model is constructed from surveyed cross sections (green line). The 2D model (orange line) is constructed with 30-meter-resolution cells (short red horizontal lines). At a 30-meter resolution, the 2D model may only capture the shape of the channel as a single lowered cell. The resulting channel shape is a much cruder representation within the 2D model.

Figure 2.8 Comparison of 1D and 2D Models in Capturing Flow Area of a 20-Meter-Wide Channel at 30-Meter Resolution

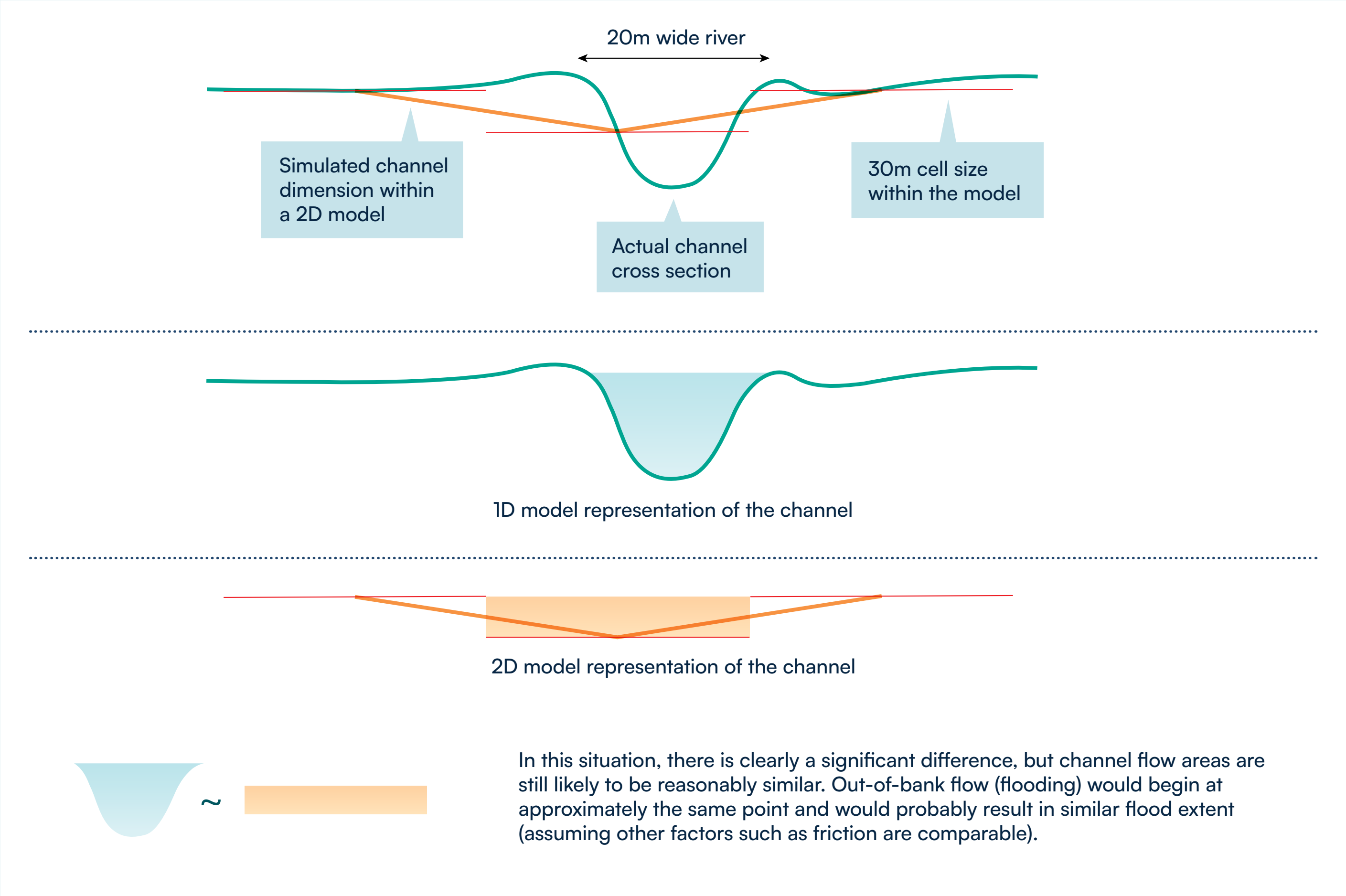


Table 2.2 offers a side-by-side comparison. In general, a Level 2 analysis would require a 2D or a 1D-2D combined modeling approach. A high-resolution accurate DTM, such as laser imaging, detection, and ranging (LiDAR), should contain most of the features that dominate flood flows, assuming the multitude of small urban drains will already be full. A 2D-only model will often suffice—an approach successfully used in many cities around the world, such as in Kampala, Uganda, with 0.5-meter LiDAR (Rentschler et al. 2019).

Larger drains and channels act in two distinct ways: (1) as floodwater conveyance, typically in areas with more gradient; and (2) as floodwater storage, typically in flat, poorly drained areas. Where the channels' conveyance capacity is an important aspect of the drainage system, it may be necessary for 1D model elements. Where storage capacity or overland flow routes are more critical, it is likely that a 2D-only model will be better. Less accurate DTMs will require more effort to capture and incorporate the hydraulically important features such as channels, culverts, bridges, and the like, and may require manual correction or adjustment.

An additional feature of a 2D model is that although it may not reflect the channel cross section as accurately as a surveyed cross section, it does capture any change in channel shape or size along its full length. With a 1D model, the channel shape and size are only captured at cross sections—often several hundred meters apart—with the assumption that the channel remains constant (or varies linearly) in between.

Table 2.2 1D versus 2D Modeling Approaches

ASPECT	1D HYDRAULIC MODELING	2D HYDRAULIC MODELING
Purpose	Best suited for in-channel flows or flows through drains, culverts, or other man-made structures. Can also be used for pluvial flood simulations in urban environments if urban topography and urban runoff are schematized appropriately.	Best suited for overland and flood flows due to coastal, riverine, and pluvial flooding, allowing for direct application of rain on grid, with many 2D models including infiltration losses. Open channel flows can be modeled in 2D if a DTM is available of sufficiently high resolution and accuracy.
Setup	Model setup generally requires more expert knowledge than a 2D model because of the schematization process (that is, the modeler needs to determine flow paths in advance). There may be more instability issues with multiple or complex compound channels, and the addition of lateral storage features may be required to account for some situations.	Model setup is relatively straightforward; however, the additional work to adjust or reprocess a poor-quality DTM can negate these benefits. A 2D model may require very small time steps, resulting in long computational time, and can be subject to instabilities in steep topography.
Topography	1D modeling requires input of the topography using a DTM for each storage node to calculate floodplain storage. The quality of the 1D model is less sensitive to the accuracy of the DTM but more dependent on the accuracy of the manual survey.	2D modeling requires an accurate DTM for the entire study area. The quality of a 2D model and its results are strongly dependent on the accuracy and resolution of the DTM.

ASPECT	1D HYDRAULIC MODELING	2D HYDRAULIC MODELING
Bathymetry of watercourses	1D modeling requires cross section data for the watercourses being modeled—typically every 50 meters for urban settings or more than 200 meters for rural settings—and this bathymetric data can be costly and time-consuming to collect. The quality of the 1D model is very dependent on the quality of these data.	Watercourse channels may be quite accurately represented by the 2D grid if the resolution is sufficiently fine (that is, more than 3 cells/channel width) and if the conveyance and storage of the channel or drain can be reasonably accurately represented by a 2D model. This is less accurate than a surveyed 1D cross section at that location but avoids the uncertainty in the interpolation carried out between measured cross sections.
Boundary conditions	Boundary conditions are normally a prederived flow or level hydrograph applied at upstream boundaries, and downstream boundaries are usually a water level, discharge rating, or extraction flow. Rainfall can be imposed at storage nodes thoughout the domain.	Boundary conditions can be the same as in 1D modeling but can often include direct rainfall across the model surface, allowing for a more detailed assessment of surface-water flooding.
Sensitivity or scenario runs	1D modeling is very suitable for sensitivity testing and doing a large range of scenario runs to test a wide variety of alternatives due to low computational demand.	Sensitivity testing and scenario runs are generally more limited because of the higher computational demands of 2D runs.
Outputs	Model outputs are point water levels or water volumes, and they generally need further intermediate processing steps to display as a flood map. This requires interpolation of the output water levels across a DTM surface.	Model outputs are normally gridded water levels and often water velocity, allowing for instant mapping of flood hazard with no intermediate processing steps.

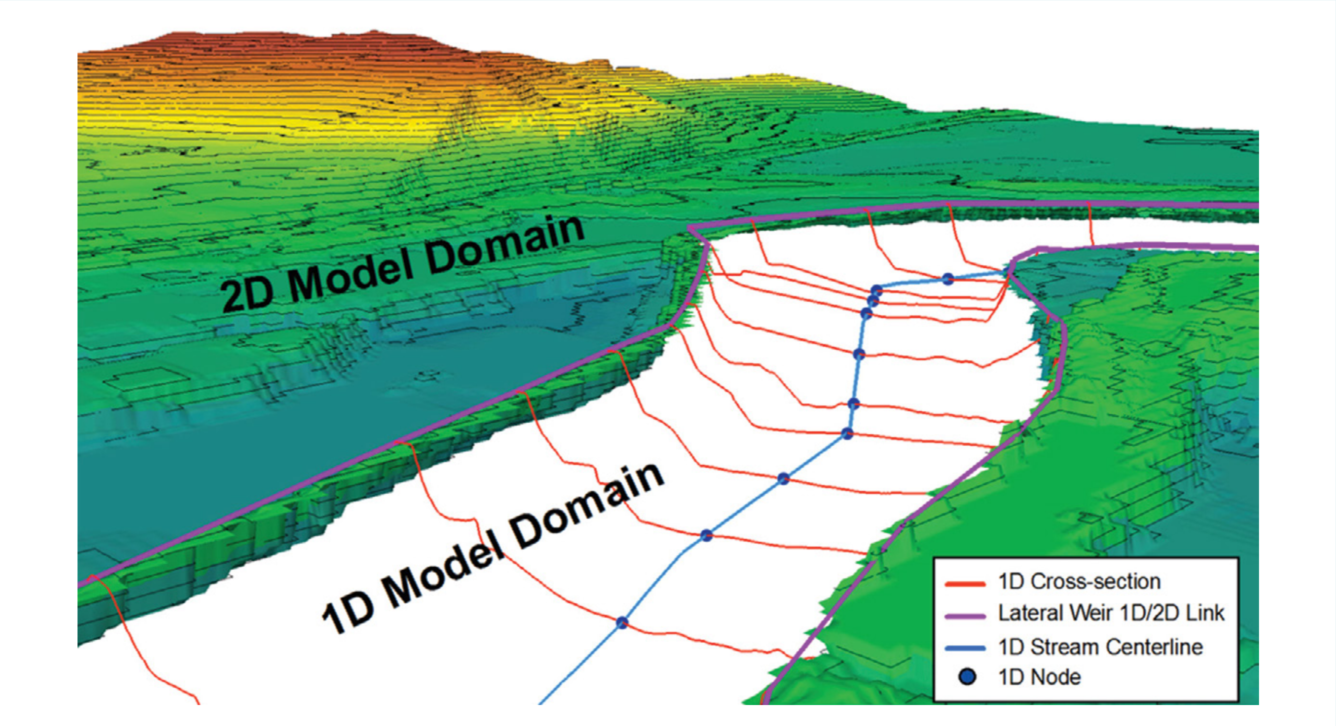
Note: DTM = digital terrain model; 1D = one-dimensional; 2D = two-dimensional.

2.3.5 Combined 1D and 2D Approach

This approach generally offers the best of both types of modeling: potentially more accurate channel definition; ability to include flow control structures, pipes, culverts, bridges, and so on; and better overland flow representation. This type of modeling, however, is more complex with significant data requirements (including channel cross sections as well as a DTM) and will take longer to develop.

Linking 1D and 2D domains is done in a variety of ways, with potentially significant differing results (figure 2.9). The vertical alignment between the 1D cross sections and the 2D grid (usually from the DTM) is critical and must use a common datum and align exactly because the transfer of water between the channel and floodplain and vice versa assumes that the channel banks in the 1D and 2D elements of the model are at the same elevation. The interface between 1D and 2D domains does not usually include the momentum term, which can result in a significant error in water transfer from one to the other. However, if carried out correctly with the right data, this approach is likely to give the best overall results.

Figure 2.9 **Schematization of a Typical Linked 1D-2D Hydraulic Model**



Source: Gilles et al. 2012. ©MDPI. Reproduced under Creative Commons license CC-BY.

Note: 1D = one-dimensional; 2D = two-dimensional.

2.3.6 Modeling Software

Modeling software would normally be selected by the consulting firm carrying out the work. Many consultants have their preferred software or may have developed their own in-house software for modeling. Benchmarking has shown that as long as the models use recognized implementations of standard equations and are developed by a specialist familiar with that specific modeling software, the results are likely to be very similar.

Well-known software packages include TUFLOW, FLO-2D, Delft3D, HEC-RAS, InfoWorks ICM, MIKE, SOBEK, SWMM, and TELEMAC. Where reuse of models or further development is required, free and open modeling software could be proposed at the tender stage, offering the advantage of either contracted or open sourcing of ongoing support and maintenance.

BOX 2.1

The Role of Different Flood Hazards in a Level 2 Flood Risk Assessment in Greater Monrovia, Liberia

A well-informed project design to reduce flood risk in an urban environment warrants a good understanding of the role and contribution of different flood hazard mechanisms to the overall risk profile. These insights are necessary to prioritize the type of interventions and also define design target levels for the structural interventions. A Level 2 assessment was therefore carried out to define a flood risk profile of Greater Monrovia with detailed hydrological and hydraulic analysis (Russell et al. 2021b).

Raised Walkways in Doe Community of Monrovia, Liberia, 2018

Source: Russell et al. 2021b. © World Bank.

Monrovia—Liberia's capital city, with around 1.5 million inhabitants—has regular floods in both housing and market areas, disrupting activities such as education, health care, and traffic to and from the city center and port area. It has low-lying, relatively flat topography with a complex system of waterbodies surrounding the city, bordered by the Atlantic Ocean to the west, the Mesurado River to the east, and the Saint Paul River to the north, which drain rainfall from the catchments in Liberia and partly in Guinea to the ocean.

Monrovia is also one of the wettest cities in the world. The average annual rainfall is 5,250 millimeters, with June and September averaging in excess of 1,000 millimeters and July and August averaging in excess of 800 millimeters. The highest recorded daily rainfall for Monrovia is 435 millimeters, while rainstorms exceeding 100 millimeters in a day are not uncommon.

A detailed two-dimensional (2D) modeling exercise with detailed topography data of the entire urban area has shown that direct rainfall flooding ("pluvial" flooding) is the most significant flood mechanism, resulting in the highest risk. The 2021 analysis also showed that the main contribution to the pluvial risk occurs during frequent events (return periods of less than 10 years). The most severe river flooding ("fluvial" flooding) affects larger areas of the city given the low-lying nature of the land, but this starts to become substantial only for relatively infrequent events (return periods of 50 years or more). Direct coastal flooding from the Atlantic Ocean is limited. However, all flood hazards will become worse in the future because of climate change effects with increasing rainfall intensity and sea level rise.

These findings, from the "Flood Risk Profile for Greater Monrovia" (Russell et al. 2021a, 2021b), have informed the project design of the World Bank's Liberia Urban Resilience Project.[a] This project specifically targets both current and future climate change risks. Informed by the Level 2 assessment, the project focuses on urban drainage improvements to reduce pluvial flood risk in targeted areas of Greater Monrovia.

a. For more details, see the Liberia Urban Resilience Project (P169718) website: https://projects.worldbank.org/en/projects-operations/project-detail/P169718.

2.4 TERRAIN AND GEOMETRY DATA

2.4.1 Digital Terrain Models

The modeling grid will be based on a DTM for the study area (figure 2.10), which provides the model with the terrain features and topography that determine where water will flow. Typically, the horizontal resolution ranges from 90 meters (Shuttle Radar Topography Mission [SRTM] or Multi-Error-Removed Improved-Terrain [MERIT]) down to 0.25 meters or less (LiDAR and DTM derived from drone imagery). In all of these products, the vertical resolution is typically 0.1 meters. The accuracy of the vertical elevations, however, can largely vary between different DTM products, from 10 meters or more to a few centimeters.

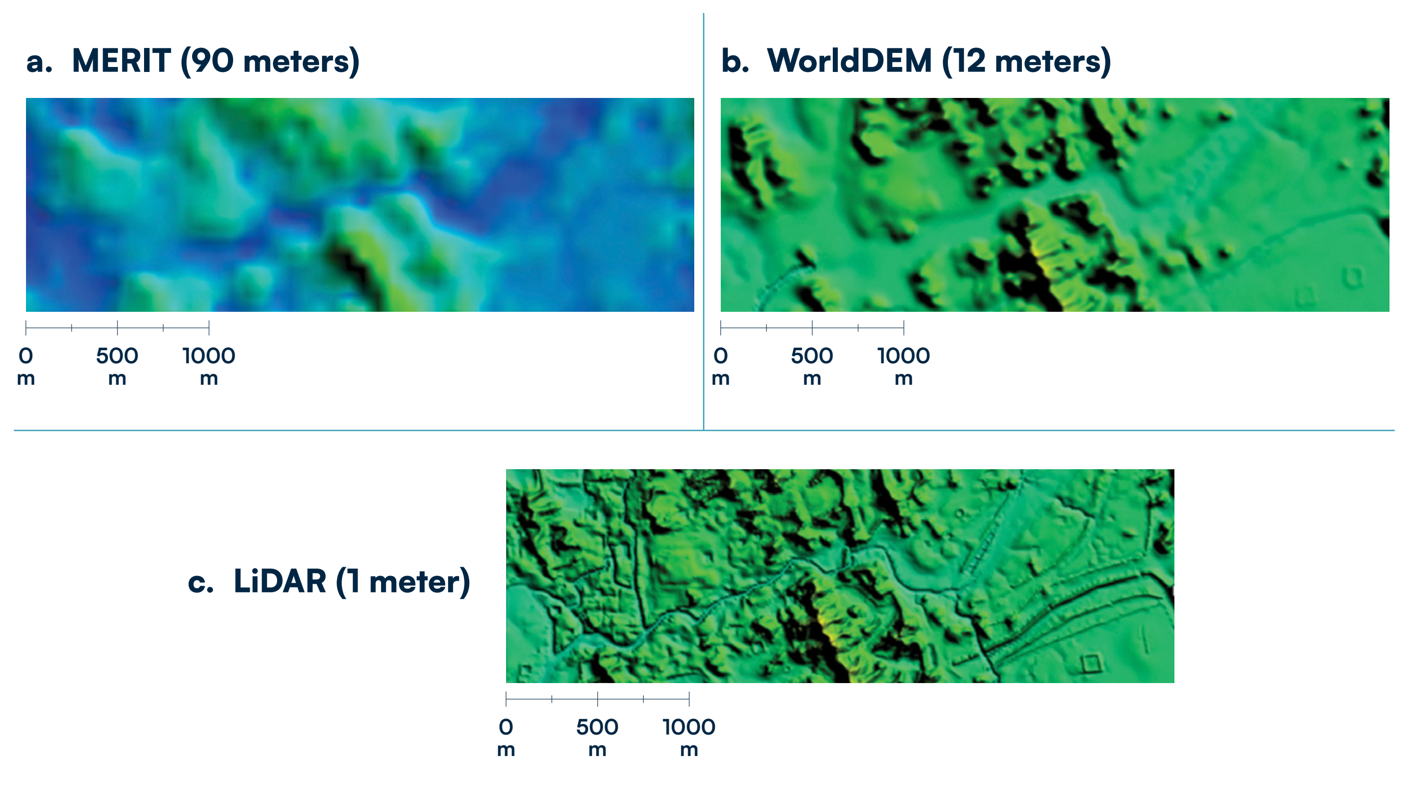
The DTM for the study area should be

- ***Consistent across the entire area of interest*** and contain no steps or breaks in elevation as these can create problems for flood modeling and will require additional processing to remove;
- ***Accurate in the vertical direction*** since topographic gradients govern flow patterns—generally, with vertical accuracy around 1 meter at minimum and preferably higher for a Level 2 assessment of an urban environment;
- ***Able to resolve flat areas,*** especially floodplains and coastal areas, avoiding contour data unless it is very high resolution (25 centimeters vertical resolution or less); and
- ***Consistent with some recognized national or international datum levels and projections,*** which is particularly relevant (1) if DTMs from different sources must be merged to provide the necessary coverage (to be avoided if possible but sometimes necessary); or (2) if the model must tie in with a coastal boundary.

DTMs based on LiDAR surveys generally provide the highest accuracy in both horizontal and vertical directions. For a Level 1 or 2 assessment, however, other less accurate options can be used. Satellite-derived DTMs with reasonable accuracy and resolution (vertical accuracy of 1 meter or better is possible in combination with sufficient ground control points) can be purchased and may suffice for a city-level study, but they usually require manual editing to enforce a hydrologically correct surface and drainage features. The freely available SRTM from the National Aeronautics and Space Administration (NASA) and similar sources such as MERIT have a vertical accuracy of 10—16 meters, which is generally considered insufficient for Level 2 flood modeling but may be suitable for Level 1 type assessments.

The DTM's vertical resolution and accuracy is important because it is a limiting factor in what can reasonably be expected in determining the characteristics of the flood hazard(s) in the assessment. For example, coastal flood levels in storm- or cyclone-prone areas typically increase by 0.3 meters to 1 meter when the return period increases by a factor of 10. Future sea level rise scenarios are also often in this same range. If the DTM has a coarse vertical resolution (for example, 0.5 meters) or is inaccurate (for example, 2 meters or more), then the extent and depth on coastal flood hazard maps derived from it will be very uncertain. In such a situation, a high-resolution DTM (0.1 meters or less) with high accuracy (for example, 0.5 meters or less) is necessary to generate accurate hazard maps.

Figure 2.10 Difference between Selected DTMs for Mrauk-U, Myanmar, 2018



Note: DTM = digital terrain model; LiDAR = light detection and ranging; MERIT = Multi-Error-Removed Improved-Terrain; WorldDEM = World Digital Elevation Model.

The vertical error of DTMs can be reduced with sufficient ground truthing and by applying a vertical correction. However, this requires additional ground surveys using high-accuracy Global Positioning System (GPS) survey equipment. Land maps are also sometimes available with detailed levels from traditional land surveying, and although these tend to be for relatively small areas, they may be preferable to satellite-based data or used in combination.

Certainty of the DTM's exact vertical datum is very important. Notably, some satellite-derived data (for example, SRTM) give levels above mean sea level that are rarely well connected to a local datum. Others will have their own—or in some cases a user-specified—datum. Verification of the vertical datum is therefore extremely important before the DTM is applied.

Possible sources for DTMs are found in table 2.3. DTM data can be one of the largest costs of a modeling exercise, but the DTM's quality and resolution are among the biggest influences on the model's accuracy. Thus, problems with the DTM are among the most common reasons for poorer than expected results or project overrun. For example, natural and man-made features—small rivers, channels, bridge constrictions, and drainage systems—may be essential for flood modeling but are not normally captured in the DTM. These may need manual or semiautomated edits to include these into the DTM. Required data of these features may be collected separately by performing bathymetric surveys or using design drawings to estimate dimensions such as cross-sectional areas and elevations.

Table 2.3 Potential DTM Data Sources for Flood Modeling

PRODUCT	CREATION METHOD	RESOLUTION (horizontal, m)	VERTICAL ACCURACY[a] (m)	MINIMUM AOI ORDER (km^2)	PRICE PER km^2 [b]	LEAD TIME[c]
Drone-derived DTM	Photogrammetric	0.2	0.4	1	$$	MM
Drone LiDAR	Laser-derived	0.2	0.4	1	$$$$	MMMM
Aircraft LiDAR	Laser-derived	0.3	0.5	100	$$$$	MMMM
Vricon-50cm	Photogrammetric	0.5	3	1,000	$$ — $$$	M / MMM
AW3D Enhanced	Photogrammetric	0.5-1-2	2	100	$$	M / MMM
Elevation1	Photogrammetric	1	3	100	$$$	M / MMM
Advanced Elevation Series	Photogrammetric	2-4-8	8	100	$$	M / MMM
AW3D Standard	Photogrammetric	2.5	5	100	$	M
Elevation4	Photogrammetric	4	4	100	$$	M / MMM
WorldDEM	Radar-derived	12	4	100	$	M / MMM
Elevation30	Photogrammetric	30	10	500	$	M / MMM
PlanetDEM	Radar-derived	30	10	100	$$	M / MMM
MERIT	Radar-derived	90	10	-	Free	Directly available

Source: World Bank.

Note: AOI = area of interest; DEM = digital elevation model; DTM = digital terrain model; km^2 = square kilometers; LiDAR = light detection and ranging; m = meters; MERIT = Multi-Error-Removed Improved-Terrain; AW3D = ALOS World three-dimensional (where ALOS = Advanced Land Observing Satellite). - = not applicable.

a. Estimated relative accuracy without ground control points (GCPs).

b. The symbols represent the following: $ = US$1 to US$25; $$ = US$26 to US$100; $$$ = US$100 to US$300; $$$$ = values greater than US$300. These prices are estimates and will vary based on the area (square kilometers) purchased, with smaller areas having the potential to be more expensive.

c. M = within 1 month; MM = 1—3 months; MMM 3—6 months; MMMM 6 months or longer. These lead times for the satellite-derived products are based on when the data exist or when the data do not exist.

2.4.2 Land Subsidence

Related to the topography of the urban environment, the role of land subsidence must always be carefully assessed in a Level 2 urban flood assessment. Subsidence of the subsoil can be a major factor in urban floods depending on the city context. Jakarta is among the well-known examples of coastal cities where land subsidence is much larger than sea level rise. Its subsidence rates exceed 10 centimeters per year (see, for example, Asmadin, Siregar, and Jaya 2021).

Land subsidence can have natural (for example, consolidation of soft deposited clays) or anthropogenic causes (such as groundwater extractions for drinking water). Its effects can change over time and in space considerably. Unfortunately, insights regarding the temporal and spatial behavior of land subsidence are generally scarce for city environments.

If subsidence is important for the urban environment under consideration, it should be factored into the flood hazard modeling approach. This can be done by either lowering the elevation of the DTM or including this subsidence in the water level boundaries for future conditions (such as sea level conditions).

Possible sources of information about subsidence include detailed local records of the national geodetic survey network. Today, detailed remote-sensing data can also provide insight into subsidence rates. The Interferometric Synthetic Aperture Radar (InSAR) technique is specifically appropriate for measuring subsidence over widespread areas with high spatial resolution. An example of application of this technique for generating subsidence information in different cities across the world can be found in a recent European Space Agency technical report (Foumelis 2020).

2.4.3 Friction

Friction is fundamental in controlling how fast water will flow over a surface. This parameter therefore determines the depth and extent of flooding a model will predict as well as the speed at which the simulated flood wave travels down a watercourse or across a floodplain, and it will affect the rate of onset and duration of flooding. “The majority of the numerical flood simulation models [1D or 2D] adopt semi-empirical equations for friction derived in the 19th century, such as the Manning, Chézy, or Darcy-Weisbach friction factor” (Bellos, Nalbantis, and Tsakiris 2018, 1). It should be noted that the Chézy formula does not vary with water depth—and, with large inundation, depths can lead to substantial errors and therefore the formula is not recommended for flood hazards. The effect of friction on water movement across a surface, often referred to as the “roughness coefficient or factor,” is dependent on the channel material or ground surface and the vegetation or other obstacles to flow, such as rocks or boulders that create turbulence.

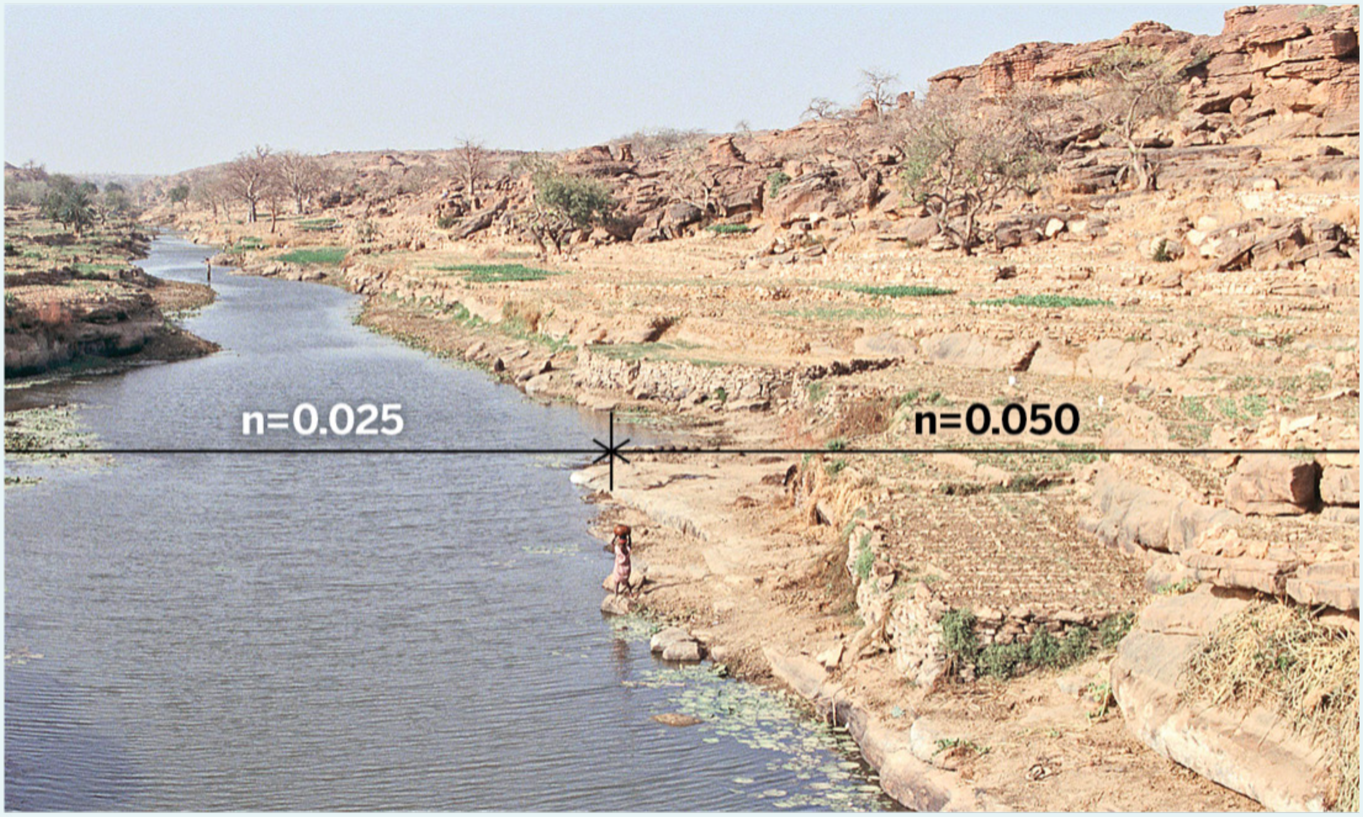
The roughness coefficient required by the model can be defined using widely available tables with descriptions of bedform or example photographs. Friction can vary considerably across floodplains and along surface-water flow routes, particularly in urban settings where roads and paved areas may provide low resistance to flow, while heavily vegetated gardens and parks may have high roughness coefficient values. Two-dimensional models often allow ***land use*** data as a GIS layer to be used as a proxy for friction. This can be a critical dataset for city-scale flood modeling.

Setting up roughness coefficient values in a 1D model can be similarly automated. However, a 1D model normally offers less flexibility for varying the roughness coefficient. Different roughness coefficient values can be used along the cross section to reflect different bed or floodplain material, but they are assumed to be constant or to vary linearly between cross sections. Therefore, it is more normal for these factors to be manually entered.

Photo 2.1 shows typical estimates for Manning’s “n”—the most commonly used factor—for a river channel and floodplain.[2] It should be noted the friction is proportional to the square of Manning’s “n,” so a doubling of the n-value equates to a four times larger friction, everything else equal. These values would be applied along the section of the cross section that represents that particular part of the channel.

Friction also changes with depth, so shallow overland flow will result in higher friction values than deep flow over the same terrain. Not all models take this into account, but increasingly some do by providing an option for entering an n-value that varies with depth (usually as a depth/n value curve).

Photo 2.1 Estimating Manning's "n"



Source: Curt Carnemark / World Bank.

Note: Manning's "n" is a coefficient that represents the roughness or friction applied to the flow by the channel. Here, the n-value of 0.025 represents a relatively low friction of the channel, and the n-value of 0.050 a relative quadrupling of friction, as represented by the surface obstacles to flow such as rocks and boulders in the floodplain.

2.4.4 Building Footprints

Buildings and solid structures such as walled compounds or enclosures affect flow paths within an urban environment, and through the process of being flooded, they can provide floodwater storage that, in turn, may change flooding in surrounding areas. It may, therefore, be necessary to include these features in the model in some way. This is normally accomplished within the 2D domain and can be done in several ways.

The simplest way may be to process the DTM that forms the basis of the 2D model in such a way that buildings and solid structures are retained. This may be reasonably accurate with a high-resolution model, but by creating a solid block, it does not account for water entering the buildings and the possible storage or attenuation of water within large areas of the city.

An alternative is to create what are sometimes termed "stubby buildings," where the footprint of the building is raised by a set amount, typically 300 millimeters, in the model DTM. This is normally done through GIS processing using the building footprint polygon for each building (which may be available through OpenStreetMap), or if the DTM has been developed using photogrammetric methods, by adding the building back into the processed DTM. This allows water to enter the building area after it reaches a certain depth. Using this method, it is common practice to use the building footprint polygons within the hydraulic model to increase the roughness coefficient (normally Manning's "n") within the building to a very high value, which allows water to enter but does not allow normal flow through the buildings.

Other methods for high-resolution models include imposing the building walls into the model and either allowing inflow through a gap in the wall or through a very high roughness coefficient again, representing porosity. Whatever process is proposed, it needs to be proportional to the benefit of the increased accuracy and must be appropriate to the scale of the modeling exercise.

Other solid and elevated structures (like elevated highways, railroads, or embankments of large drainage canals) must also be checked because these may substantially affect flow patterns in urban environments. For these structures, a similar approach can be adopted as for buildings. Openings in these solid structures (for example, large viaducts or overpasses) must be included because these can be important water exchange pathways.

2.4.5 Urban Drainage Systems

Natural and man-made water infrastructure—channels, rivers, ponds, wetlands, culverts, bridges, and the like—can be essential for modeling urban floods but are not usually captured in the DTM. Underground stormwater and sewage pipe systems are by default not available in a terrain model. Urban drainage systems, especially in older cities and settlements, can include systems and structures from several different eras of a city's development, the original purpose of which may now be lost or unknown. Examples could include ancient or modern irrigation systems, culverted rivers, mill streams (leats), fish ponds, reservoirs, and cisterns. More recent changes may also have occurred in how surface water is managed—for example, as peri-urban areas become urbanized or where sustainable drainage systems are adopted into design practices.

It is usually not necessary to include the full urban drainage system within a model for a Level 2 analysis. For each context, it is advisable to initially screen which elements of the urban drainage system must be modeled explicitly and which parts can be either neglected or included in a such a way that the overall effect is correctly included. Data collection of drainage systems and other relevant infrastructure is often time-consuming and costly. Use of data from earlier studies, surveys, and the like, or a rapid assessment as part of the project, can provide a viable option to avoid or limit a detailed survey. A single photograph of the upstream face of a bridge or culvert (with a measuring staff included to provide scale) can often provide most if not all of the data required.

Where many small drains exist, particularly subsurface or roadside drains, it is usually possible to implement modeling techniques that can simulate the overall drainage effect without having to include all of the detail, which may not exist or would be costly to collect. This simulation can take the form of removal of a certain percentage of the amount of rainfall or inflow to account for the water likely to be retained within the drains and will therefore not result in surface-water flooding.

The importance of the existing natural and man-made infrastructure, whether aboveground or underground, depends very much on the extent or capacity of the system as well as the type of flooding—for example, a coastal flood overwhelming the city, as opposed to a localized pluvial flood where insufficient drainage is the main cause. Also, during large flood events, these systems and their management are often relatively insignificant as they will be overwhelmed by the floodwater, and in reality, their design or condition means they have little influence on the depth, location, and extent of flooding and can usually be ignored in a city-scale assessment.

However, there may be some instances or locations within a city where the local drainage can be significant in determining flood hazard and risk. In these instances, more detailed Level 3 modeling may be required to achieve sufficient confidence in specific areas of the assessment. If this is known in advance, Level 3 modeling can be incorporated as part of the overall citywide Level 2 assessment. But if the need comes to light only after the Level 2 assessment, the Level 3 modeling may be required as either an ***add-on*** to the assessment or as a separate study to be carried out as part of the feasibility and cost-benefit analysis before design.

Where significant asset data collection is required, this may contribute additional benefits beyond the modeling study. For example, asset surveys using georeferencing data to capture the location, dimensions, materials, and conditions of assets can be used by the municipality or other competent authority to plan maintenance, rehabilitation, or expansion of drainage systems.

BOX 2.2

Selection of a Flood Hazard Modeling Approach for Greater Paramaribo, Suriname

The strategic flood risk assessment carried out for Greater Paramaribo, the capital city of Suriname, provides a good example of the decision process, choices, and compromises that must be made in selecting an approach to modeling the flood hazard for a city. The purpose of the study was to support the development of a prioritized flood risk management investment plan for the city and surrounding areas. It therefore was important to understand the main flood issues and dynamics of the flooding, as well as how the various sources and types of flooding affected the city and its occupants. Other factors that determined the scale and depth of the study were the available data, the budget, and the time frame, which was a little under a year.

The flood hazard affecting the area was relatively complex, with a mix of tidal influence and extensive pluvial inundation, over the very flat and low-lying coastal plain where Paramaribo lies on the banks of the tidally influenced Suriname River. The city is drained by a complex network of canals, which drain mainly either to the river, the coast, or into the Saramacca Canal, which runs from east to west through the southern portion of the city.

Saramacca Canal in Paramaribo, Suriname, 2017

Source: © Scott Ferguson / World Bank.

As is often the case, the availability of rainfall records of sufficient length for statistical analysis was limited; they consisted mostly of daily totals, collected by the Suriname Meteorological Service using manually read storage gauges. While extremely valuable, these daily totals do not provide the detailed resolution of intense bursts of heavy rainfall that is often key in understanding urban flooding. However, a small number of automatic rain gauges with a few years of records provided some evidence of critical storm duration for frequent events and a means of disaggregating the daily records into critical-duration design storms.[a]

An additional factor was the availability of a digital terrain model (DTM), which is essential for a citywide flood modeling exercise. Although freely available DTMs—such as the National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (STRM) data or, more recently, the improved Multi-Error-Removed Improved-Terrain (MERIT) data—have a useful role in preliminary flood hazard assessment, particularly when large rivers are involved, they do not provide the necessary resolution for city-level studies where the detailed flow paths are critical. Because of limitations in budget and time, a compromise between the best available DTM captured using laser imaging, detection, and ranging (LiDAR) and the low-resolution satellite-derived data was agreed upon, and the Airbus WorldDEM 12-meter resolution data was purchased.

The extensive network of canals that help drain the city during flood events are important in two ways: they provide storage for the floodwater during an event, and they improve conveyance of floodwater away from vulnerable areas. A key and sometimes difficult decision regarding the modeling method is how to best to represent channels and canals and their influence on drainage. The best way, particularly in a low-lying, flat area such as Paramaribo, is a combined 1D-2D hydraulic model that captures both the channel flow and the overland flooding. However, this requires accurate channel bathymetry (cross sections) survey and processing, which can be a very time-consuming and costly process. In the case of Paramaribo, it was decided for both practical and technical reasons that a 2D-only model using a hydraulically corrected DTM (that is, the canals were artificially carved into the DTM surface) could reflect the canals sufficiently well to achieve the purpose of the study.

The modeling assessment provided the study with a tool that enabled quantified, risk-based testing of various mitigation options, including canal improvement works, additional pumped discharge at the coast, improvements to the Saramacca Canal, and coastal defense works.

The study has successfully led to a project—the World Bank's Saramacca Canal System Rehabilitation Project[b]—that aims to reduce flood risks by upgrading critical drainage infrastructure of the canal and other secondary and tertiary systems, optimizing the use and maintenance of the canal (providing additional navigation improvements), and updating norms and guidelines for drainage management, among others.

a. A "design storm" refers to a hypothetical depth of rainfall that occurs at a stated return period, duration, and timing of distribution, based on an area's historical rainfall records. For further definition, see the glossary.

b. For more details, see the Saramacca Canal System Rehabilitation Project (P165973) website: https://projects.worldbank.org/en/projects-operations/project-detail/P165973.

2.5 CALIBRATION AND VALIDATION

Once the hydrological analysis and hydraulic models have been set up and appropriate boundary conditions have been established, the flood hazard model must be calibrated and validated. A strategy for "calibration" (the use of recorded data to define model parameters) and "validation" (the use of recorded data to check model validity) of the flood hazard modeling is key to obtaining credible hazard maps and to understanding potential weaknesses and uncertainty. Different sources of calibration or validation data for flood hazard models are

- ***Hydrometeorological data:*** records of water levels, river discharge, and so on;
- ***Flood depth or water marks:*** observed high water levels following an event;
- ***Community surveys:*** not only locations and depth but also indications of frequency, flood duration, timing of arrival, and so on;
- ***Satellite information (such as Copernicus):*** useful to define the flood extent but challenging for urban environments;
- ***Online information:*** media reports and social media information such as FloodTags (weather impact monitoring using social media) with event-specific information;
- ***Disaster databases:*** disaggregated records of historical damages and losses (such as DesInventar and EM-DAT);[3] and
- ***Post disaster needs assessments (PDNAs):*** assessments carried out after major disasters to build an accurate understanding of the events and their impacts and develop a prioritized medium- to long-term plan for recovery and future mitigation. A PDNA is normally conducted as soon as possible after the event to capture as much data as possible before they are lost or forgotten.

It is important to recognize that all observational and modeled data from hindcast models used in flood hazard modeling have their limitations that affect how these data can be used for modeling, calibration, and validation. For example, floodwater marks at exposed locations often include the effect of short waves on top of the still water level, whereas these waves are not always included in large-scale flood hazard modeling. Thus, a direct comparison between these observations and the model output is only useful if this effect is accounted for. Another issue could be that the hindcast meteorological data used for modeling input data do not capture small-scale variations in the local weather conditions, and the modeling input is therefore not directly comparable with observational data from one location in the area of interest. These issues in both the observational and modeled data must be identified and understood when modeling outputs are compared to observations.

Generally speaking, the amount of calibration or validation data for flood hazard mapping is limited because of the lack of a well-functioning water monitoring system in many countries. Therefore, collecting secondary information in data-poor environments is always recommended, and it requires creativity in combining different primary and secondary data sources to check the modeling results. Using common sense to review the final results—by checking affected populations for very frequent events—is important to arriving at realistic results.

2.6

IMPORTANCE OF SENSITIVITY ANALYSIS

Given the significant level of uncertainty within the overall modeling and analysis process, it is important to consider the possible sources and consequences of these uncertainties and how they might influence any decisions made based on the results. One relatively simple and common approach is to carry out a sensitivity analysis to understand the contribution of different factors to the total uncertainty. This analysis investigates the key parameters or input variables of the model by systematically varying each in turn over a range of possible values. The range will usually include unlikely extreme values as well as more realistic values that may be close to the actual selected values.

The purpose of the assessment is to see the effect that each parameter or input variable has on the outcome and how sensitive the outcome is to a particular parameter or input. It is important to note that any given percentage change in one part of the system (that is, in input variable or a modeling parameter) is unlikely to have the same percentage change in the output for any of the flood scenarios investigated. Carrying out this analysis helps pinpoint the significant sources of uncertainty within the process, allowing appropriate actions to be taken to reduce the uncertainty or to recognize the likely scale of the uncertainty and incorporate that uncertainty into the decision-making process.

A simple example could be where there is only limited rainfall data available for a study, resulting in a large uncertainty around the design event scale and return periods. Running the model multiple times—with perhaps up to plus or minus 50 percent of the estimated event rainfall—will show how much of an impact could result from making an incorrect estimate or assumption about the rainfall. It may also highlight any notable nonlinear responses these types of systems often exhibit, where a change in the input does not necessarily result in a similar change in the output—in this example, the flood extent. In reality, the outline of flooding might be quite constrained up to a certain rainfall total, but above a certain value, the flood extent may become much larger in response to a relatively small increase in rainfall. Understanding this and knowing the scale of event where this nonlinearity might appear could be very important when interpreting the model results, revealing where uncertainty might be most significant and perhaps where it is worth investing more effort in improving the confidence in the model parameter or input variable.

There are many parts of the assessment where sensitivity analysis could be carried out, but the selection of parameters or variables will need to depend on some local knowledge as well as professional judgment to determine where the most significant uncertainties lie. Common parameters besides rainfall that would normally be subject to sensitivity analysis for the flood modeling process would include: (1) Mannings “n” (the model friction coefficient), which is often quite subjective and often more spatially variable than the model usually allows; and (2) infiltration rates that depend on a number of factors such as soil type and land cover and is at best an average over any area.

Further sensitivity analysis would often be carried out at other stages of the overall risk assessment process, investigating the impact of uncertainty in both the exposure and the vulnerability factors.

2.7

FLOOD HAZARD SIMULATION — SCENARIOS AND MAPPING

A well-calibrated and validated flood model is a useful tool for investigating different scenarios and preparing flood hazard maps. It is necessary to establish a baseline of flood scenarios against which mitigation options can be tested to understand and deal with flood risk both now and in the future and assess the benefits of these possible mitigation solutions. This baseline will consist of the range of possible events and impacts that could occur, some more likely than others that represent the current situation.

There is often significant uncertainty in the future scenarios, which must be recognized throughout the entire flood hazard and risk assessment (see, for example, Hallegatte et al. 2012) and quantified where possible. The future scenarios should include, as a minimum, a range of event severity, relevant climate change factors, subsidence, urban growth, and land use change. It is likely that not all of these, and potentially others, will be equally significant and may be assessed in a sensitivity analysis, while others are more relevant and will require more in-depth analysis. By analyzing these scenarios and quantifying the impacts through some form of modeling, a baseline envelope of potential realities can be developed, which, although uncertain, will provide a basis for making or prioritizing difficult management choices.

Generally, a range of return periods is selected in a Level 2 assignment to define the potential hazard for the baseline and the future scenarios (that is, a "semi-probabilistic approach"; see also the earlier "Flood Hazard Probabilistic Assessment" section). It is important to note that low return periods (such as one or two years) can contribute significantly to the overall risk because these floods occur most frequently. However, these small events are likely to contain the most uncertainty because of the lack of resolution within the model. For example, minor errors in the DTM could make the difference between relatively shallow but frequent flooding occurring or not. Extra care should therefore be taken to ensure these events are as accurately reflected as reasonably possible. High return periods of 100 years or 250 years are also necessary to include the impact of unlikely but potentially catastrophic events. These extremes are also prone to large errors because of lack of historical data and difficulties in obtaining accurate measurements. Where the impact of an extreme event is thought to be potentially catastrophic, as in a dam breach, it is normal to consider very unlikely but still possible events—that is, up to a 1,000-year event or even higher.

Future scenarios will always be required as part of a Level 2 assessment, including potential changes not only in the physical system (for example, sea level rise, subsidence, and so on) but also in the urban context (such as urban growth and land use change scenarios). A sufficiently long time horizon must be adopted (for example, 25 or 50 years) for these future scenarios because most interventions, particularly structural interventions, are typically built to last for decades. Global climate models can provide an indication of the likely direction and extent of changes at these time scales.

Those developing flood risk solutions need to account for the range of changes in key parameters derived from projections from more than one climate model. The World Bank's Climate Change Knowledge Portal allows for this.[4] Selection of the most important variables for flood risk is important. For example, selecting a rainfall change with a 50-year return period will be more informative than looking at the seasonal rainfall total change, though both variables may be useful. In certain situations, dichotomies can exist; for example, annual rainfall may be expected to decrease in a certain location, but because of higher temperatures, the intensity of rainfall during storms may increase.

Finally, it is important to ensure that the presentation and visualization of flood hazard data are carefully considered to allow nonspecialists and decision-makers as well as technical experts to understand the information contained within the analytical flood hazard results. Maps of the maximum flood or time-dependent animations of flood scenarios are not only indispensable tools for supporting discussion among experts but also communication tools for engagement with the wider group of stakeholders. The contents, scale, and color schemes need to be tailored to the specific audience and discussion topic within the assignment for which these visualizations are used.

Often, flood depth maps are widely used to show the severity of the flooding. But in certain situations, flood velocity maps can be useful (for example, in hilly urban environments) to identify areas with dangerously high flow velocity. Also, flood propagation maps showing the time of flood arrival can be useful to evaluate the potential for emergency measures. Scale and color schemes must also be defined with care because these could also lead to misinterpretation, especially since specific colors may have different interpretations. Good practices from the flood hazard mapping within the framework of the EU Directive 2007/60/EC, "on the Assessment and Management of Flood Risks" (EU 2007), may provide inspiration for thinking carefully about visualizations that convey the right message to the targeted audience (Martini and Loats 2007).

2.8 FLOOD HAZARD PROBABILISTIC ASSESSMENT

As outlined in chapter 1, a full probabilistic approach in a hazard analysis is not commonly used in a Level 2 assessment, but this approach can provide several benefits. A brief synopsis is provided here of what a full probabilistic approach for flood hazard modeling entails and the kinds of outputs and information such an analysis may generate. Analyzing the flood hazard and the impacts as well as the benefits of potential measures—based on a lengthy synthetic time series of genuinely potential weather or tides, for example, rather than on a small set (typically around six to eight) of artificial design events—will generally result in a much more robust risk assessment and options appraisal. Because such an approach is generally more time-consuming and also (much) more computer-intensive, the added value of a full probabilistic assessment for a Level 2 assignment must be weighed carefully to establish an efficient but still robust modeling approach.

A full probabilistic assessment generally requires synthetic time series (say, 10,000 years) of conditions of the relevant flood sources and state conditions (such as rainfall, tide levels, and antecedent soil moisture conditions). Because 10,000 years of climate or flood data clearly do not exist, time series analysis methods like Monte Carlo simulation or numerical integration are used to develop the input data. This synthetic record will include the spatial as well as temporal variation of all conditions that could result in flooding, such as combinations of different parts of tides;

long-duration, low-intensity rainfall; high-intensity events; seasonal fluctuations in groundwater, river levels, and soil moisture content; and so on. The detailed methodology for this process in this type of assessment is less well established than the more traditional approach and will vary depending on the supplier's expertise and knowledge. When considering this approach, it may be more effective to specify the outcomes than to be too prescriptive about the methodology.

Probabilistic hazard event sets will typically contain 10,000 years or more of synthetic events, but to capture the variability of all the relevant factors, it is important that they be derived from recorded data that capture the broad spectrum of variables and are of sufficient length to be statistically meaningful. Global datasets (such as ERA5) adjusted using local records, however short, are increasingly making this approach more feasible. This method must be clearly defined by the consultants carrying out the work.

Depending on the method chosen, it may be possible to go directly to a probabilistic analysis and develop flood maps for any given return period. It is common, however, to use the deterministic events with different return periods described in previous sections and use those data to help define the probabilistic hazard data through look-up tables based on these events. A probabilistic approach can include the fitting of joint probability distributions to extremes at, for example, multiple rain gauges (Tawn et al. 2018). This permits the generation of synthetic rainstorms having realistic spatial distributions. Rainfall-runoff modeling translates the rainfall into river flows at key nodes with associated severity based on frequency analysis.

Synthetic time series add value in several ways:

- Meteorological characteristics such as rainfall typically show a large variability, which can be lost in short periods of record. This inevitable limitation of historical records will affect risk assessment.
- If implemented well, a synthetic time series is a method to overcome these potential shortcomings, especially if the synthetic time series is long enough (for example, 10,000 years) and will contain substantially more extremes than observed historical records.
- Synthetic time series will also contain many different variations and spatial configurations of essentially the same design event (for example, a 20-, 50-, or 100-year flood event), allowing for estimation of a wide range of possible spatially varying, and in some cases cumulating, risk metrics.

It is noted that generating these long synthetic time series is not straightforward and can be quite computer demanding in specific environments. For coastal environments, for instance, long time series with nearshore tides, storm surge, and nearshore waves due to tropical weather systems cannot be derived statistically from global datasets because the weather systems are not well captured in these models. Hence, detailed coastal modeling would first be required to derive synthetic time series of input boundary conditions that include a proper spatial and temporal distribution of the storm surge and nearshore waves. For these environments, statistical sampling of data produced from different sources (for example, models and observations) of tidal and nontidal water levels and associated waves may be suitable and a more efficient approach.

Outputs from a full probabilistic flood hazard assessment would typically be gridded datasets of flood depth and probability as well as the gridded depth for any given return period. This output includes more information than a semi-probabilistic assessment in that it provides a continuous flood frequency curve for the entire domain in space rather than only the results of discrete extreme events at each output location. It may also be a requirement (for large study areas) to provide statistics for the probability of multiple events of a given probability occurring at a given frequency—for example, the likelihood that a large river basin could experience several independent events, at the same time or in a single year, that are greater than 10-year return period events. Only a full probabilistic assessment can address these types of questions.

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ENDNOTES

1 The remote-sensing product abbreviations refer to Multi-Source Weighted-Ensemble Precipitation (MSWEP); Tropical Rainfall Measuring Mission (TRMM); Global Precipitation Measurement (GPM); ECMRF Reanalysis v5 (ERA5); and Climate Hazards Group InfraRed Precipitation (CHIRPS).

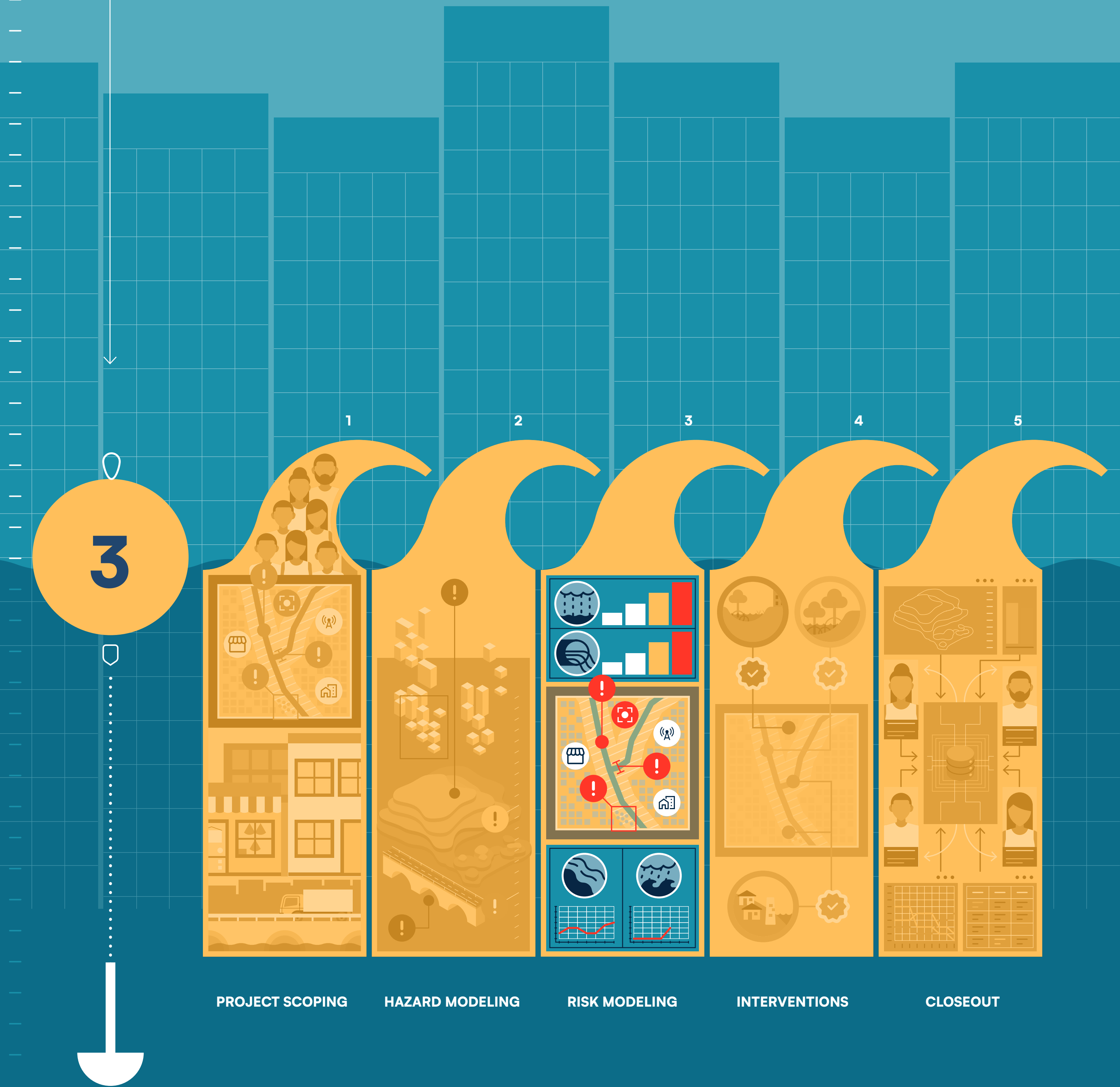
2 Manning's "n" is a coefficient that represents the roughness or friction applied to the flow by the channel. Manning's n-values are often selected from tables but can be back-calculated from field measurements.

3 DesInventar (https://www.desinventar.net/) is a disaster information management system—hosted and primarily sponsored by the United Nations Office for Disaster Risk Reduction (UNDRR)— that can be used as a tool to generate national disaster inventories and build databases of damage, losses, and other effects of disasters. EM-DAT, the international disasters database (https://www.emdat.be/), is provided by the Centre for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain, Brussels. Providing an objective basis for vulnerability assessment and decision-making in disaster situations, it provides information on the human impact of disasters as well as disaster-related economic damage estimates and disaster-specific international aid contributions.

4 For more information, see the World Bank's Climate Change Knowledge Portal website: https://climateknowledgeportal.worldbank.org/.

CHAPTER

FLOOD RISK ASSESSMENT



3.1

INTRODUCTION

Flood risk assessments investigate and, where possible, quantify the potential consequences of flooding from all sources to the exposed assets and the population across a given area. To understand and quantify the risk associated with flooding, it is necessary to capture not just the three components that determine the scale of the impact—hazard (extent, depth); exposure; and vulnerability (figure 3.1)—but also the likelihood (or probability) of impacts for a range of possible conditions.

Especially in an urban environment, the risk of flooding is a complex phenomenon. Such an environment contains many different asset types (public and private buildings as well as various types of infrastructure such as roads, railroads, water supply, and so on) and population groups (for instance, females, males, children, and elderly populations; different ethnic or religious groups; and a range of socioeconomic statuses). Each of these exposed assets and population groups have different vulnerability to floods. A flood risk assessment must take into account all dimensions.

Several considerations are important for this type of assessment:

- **What is the purpose of the risk assessment, and how will the outputs be used and by whom?**
- **What are the relevant types of consequences?**
- **What is the appropriate risk modeling approach given the available hazard, exposure, and vulnerability data?**
- **Which data sources are suitable to assess the exposed population, assets, etc.?**
- **What information is available on the vulnerability of risk receptors?**
- **How should risk models be calibrated or validated?**
- **Which scenarios must be evaluated to get a robust insight into the current and future risks?**

Keeping the aim of the risk assessment and the end users of the outputs in mind is essential throughout the assessment's setup and execution. As outlined in the Overview (figure O.2), the ultimate goal of a Level 2 assessment is usually to help define and guide decisions on intervention strategies for a specific urban context to mitigate the risks of flooding. By nature, such an assessment should always have a forward-looking approach that includes climate change and urban growth projections.

It is also important to be clear on how and by whom the results will be used. This may put specific requirements on the production and presentation of the risk assessment results and which specific aspects must be addressed in a specific context. Having this conversation early in the process will help ensure that the risk results are understood and support the decision-making process.

Figure 3.1 Components of Flood Risk

One of the most useful and key outputs of a flood risk assessment is the enumeration of damages and losses and affected population. These are often expressed as annualized values, normally presented either as gridded values distributed across the study area or as an integrated risk value for an entire given area (for example, municipal boundary or sub-basin). Damage and losses can also be calculated for each individual element in the exposure inventory or group of sectors (health, education, agriculture, public, private, and so on), economic activities, or income sources. Similarly, it is useful to calculate the impacts of floods to different population groups based on sex, income level and age.

The terms “losses” and “damages” are often used interchangeably. More correctly, however, “damages” refers to the direct cost of physical damage to buildings, contents, infrastructure, and the like, whereas “losses” refers to indirect impacts on the economy such as lost revenue or income due to commercial operations being limited, or lost productivity due to health issues, and so on.

Gridded data of the risk metrics can normally be achieved at a relatively high spatial resolution (potentially 100 meters by 100 meters). These can easily be aggregated to wards, districts, local government areas, river basin units, or any user-defined polygons that can be derived for multiples or subsets of the aforementioned. They should provide sufficient granularity to assess the effects of different exposure or vulnerability factors such as poverty and local resilience on aspects such as recovery rate, and how these effects may influence the distribution of flood risk. There will inevitably be differences in the exact definition or interpretation of these risk metrics. However, as long as the definitions are clearly defined and agreed upon, the simplest commonsense approach should always be adopted that makes the best use of the data available for a Level 2 assessment.

BOX 3.1

Probabilistic Flood Risk Assessment for Zanzibar City and Dar es Salaam, Tanzania

A flood risk assessment was carried out between January 2020 and January 2023 by the World Bank for the Tanzanian cities of Dar es Salaam and Zanzibar City on the nearby island of Unguja (World Bank 2023). Its objective was to provide the Bank with a robust and defendable set of current and future hazard and risk data and mapping to support the Tanzanian government in improving risk management.

Although the assessment was relatively standard in many technical aspects, a fully probabilistic assessment was conducted because of the quantity and, more importantly, quality of existing spatial data available to the study as well as the requirement for a more in-depth understanding of risk in a city that was suffering increasingly frequent and damaging flooding.

The fully probabilistic risk assessment approach would provide a much richer risk assessment than the “deterministic” approach because it captures the real variability in flood-generating events and the vast range of weather and climate dynamics behind these events.[a] Rainstorms of any significant magnitude do not occur uniformly over an entire city as large as Dar es Salaam, and the sub-basins that drain into and through the city will all respond and combine differently in every storm. A rainstorm can occur in combination with different starting soil moisture conditions and sea levels, which will also affect the catchment response to the rain. This makes interpretation of the annual average damage or losses for an entire city difficult if it is derived using a deterministic approach—that is, using a range of return periods (such as 2 years, 10 years, 50 years, 100 years, or 200 years) that assumes the same severity of event over the entire city.

The fully probabilistic assessment was carried out using a derived event set consisting of 10,000 years of synthetic rainfall depths, soil moisture states (estimated from antecedent precipitation), and tide levels. These events were derived through a statistical analysis of all the available data for the region, of different sources, lengths of record, and spatial and temporal resolutions.

Ideally, these series would be used as input for the hydrological or hydraulic model to derive a 10,000-year synthetic series of river flows and flood depths. However, this was not feasible in terms of the model simulation time. Therefore, to save computation time, a “lookup table” was used that contained results from hydrological or hydraulic model simulations of a set of predefined synthetic events of combinations of rainfall, tide, and soil moisture. For each day in the 10,000-year series, the flood risk at each grid cell is estimated by looking up the simulation results of the event in the lookup table that most resemble the generated hydrometeorological conditions of the day.

The output of this modeling consisted of a set of genuinely distributed risk maps considering all relevant flood events in the 10,000-year synthetic time series. A key difference between these probabilistic maps and more traditional deterministic hazard maps is the fullness of the data they contain. They can provide a risk or hazard probability curve at every point on the map, giving the complete picture of flood risk across the city.

These maps can be used to quantify flood risk across the city, providing the usual metrics of average annual loss (AAL) and probable maximum loss (PML), but instead of being limited to either annualized results or single return period results, it is possible to map the probability of any event and its impacts at any location across the city. This provides a powerful tool in helping understand and manage risk within a city.

Flooding in Dar es Salaam, Tanzania

Source: © Chris Morgan.

a For a further general description of deterministic versus probabilistic approaches to flood risk modeling, see chapter 1.

3.2 CONSEQUENCES

Risk quantification starts with recognizing different types of impacts from an urban flood event. Affected population, damage to assets, economic losses, and environmental and cultural damage are key consequences in any flood situation (as summarized in chapter 1, figure 1.4.) Consequences are often categorized in two ways (table 3.1)—based on the difference between (1) tangible and intangible damages, and (2) direct and indirect damages, resulting in four possible groupings. They are not always clear-cut, and there is some flexibility between the groups, but the distinctions are useful because they can support not only the quantification of relevant consequences in a specific context but also how best to quantify them.

Table 3.1 Examples of Flood Damage, by Type

FORM OF DAMAGE	MEASUREMENT	
	TANGIBLE	INTANGIBLE
Direct	Physical damage to assets: Buildings Structures Vehicles	Loss of life Loss of cultural heritage Loss of ecological goods
Indirect	Business interruption Welfare losses Short-term and long-term delays	Long-term environmental impacts (for example, loss of fisheries) Social impacts such as those from anxiety or stress Gender- and age-specific hardships Short- and long-term health effects

Source: Adapted from the FLOODsite Integrated Project, "Task 9: Guidelines for Socio-Economic Damage Evaluation," http://www.floodsite.net/html/work_programme_detail.asp?taskID=9.

The horizontal axis in table 3.1 categorizes flood impacts as either tangible or intangible damage. Tangible damages are those that would be easily measurable in monetary terms. Intangible damages relate to those impacts that are far more difficult or even impossible to quantify. For example, the floodwater damage to a building could be directly quantified (that is, the cost of repair) and is considered tangible. Suffering and hardship due to flooding as well as mental or physical health problems are also direct results, but they cannot be quantified in monetary terms and are therefore intangible.

The vertical categorization in table 3.1 is between direct and indirect damages and losses. The impact on the health of individuals as a result of flooding (injuries, loss of life) may be a direct consequence of a flood. However, the loss to the economy due to reduced economic production would be considered indirect—although still tangible because it is measurable and specific to the flooding event.

When doing a Level 2 risk assessment, it is important to identify which consequences are relevant to include and whether and how these can be quantified. In general, the most robust risk quantification models have been developed for direct, tangible damages. Models for indirect, tangible damages also exist to quantify the damages due to business and transport interruption. The uncertainty of models for indirect, tangible damage is generally much larger because of the many interactions and data requirements involved. Also, combined modeling strategies have been proposed allowing for the dynamic losses from a flood event (see, for example, Koks et al. 2014).

Intangible damage is by definition hard to monetize, but these consequences can be estimated in other terms (such as number of people injured or casualties). It is important to highlight that some risks can be sensitive to address in a specific context (including loss of life and consequences to specific objects such as cultural heritage).

3.3 ASSESSMENT SELECTION AND DATA REQUIREMENTS

The risk modeling choice depends on the required level of assessment (as summarized in the framework shown in chapter 1, figure O.2). Factors governing this choice, among others, are project development stage and objective; relevant types of risk receptors and the consequences; availability of data and possibility of data collection; and available time and budget. For screening purposes (Level 1), spatial quantification of the number of exposed assets and population may be sufficient. For a detailed assessment (Level 3), robust quantification of all damages (including intangible), as well as direct and indirect impacts, will be required as input for the cost-benefit analysis, feasibility, and design.

A strategic flood risk assessment (Level 2), which is the subject of this handbook, requires a spatial quantification of tangible (and, where possible, intangible) impacts, and must consider both direct and indirect impacts. Two approaches to exposure and vulnerability for quantifying the risks to assets are commonly used: area-based and asset-specific.

Area-based assessment. Under this approach, an approximation of the area covered by specific land uses is made as follows:

- This approach usually uses a combination of satellite imagery, available land use maps, and local knowledge, with polygons created around communities or neighborhoods and commercial or industrial districts. It does not look at individual assets like public and private buildings, hospitals, roads, or railways within an area.
- The data can be gridded to reasonably high-resolution grid data (such as 100 meters), where an average of the land use type is assigned to each grid cell, and an average flood depth across that particular cell is used for the depth damage calculation. The percentage of overall area assumed to be assets needs to be estimated—often from satellite imagery.
- A high level of uncertainty relates to inundation depth associated with specific buildings (that is, the assessment does not distinguish between open ground or a building within the area) or other assets, but on average, the results can be reasonable.

- The damage calculations can be carried out using vulnerability curves in combination with area-based maximum damage values (using, for example, US dollars per square meter) for which global datasets are available, such as the ones reported by the European Commission's Joint Research Centre (JRC) (Huizinga, de Moel, and Szewczyk 2017). These calculations can be fine-tuned based on local knowledge or expert views.

Asset-specific assessment. This approach may be more onerous, attempting to identify all individual at-risk buildings and other assets and allocate a specific use or type, as follows:

- Local OpenStreetMap (OSM) initiatives and emerging satellite image processing algorithms mean that individual building outlines and building types as well as other assets can be created through partially automated processes or may already be available from cadastre-type government data.
- This approach is more accurate for flood inundation to specific assets but is still dependent on high-quality land use or building type data. Data would not normally be gridded, and inundation depth would be attributed directly from the hazard layer. The results, however, would be processed through a standard geographic information system (GIS), and the outputs would be gridded at any resolution required.
- The damage calculations follow the same procedure as area-based assessments with use of a vulnerability function. For a building-specific assessment or other built-up assets like infrastructure, these damage calculations can use the flood hazard information in two ways: (1) using an average depth across the area of the polygon that represents the building footprint, in which case the calculation also uses the area (or size) of the building; or (2) using the simulated flood depth at the center of the building.

Both the asset-based and asset-specific approaches may use global data such as from the JRC (Huizinga, de Moel, and Szewczyk 2017), but it is always better where feasible to combine these global data with local, more representative information to reduce the potentially large uncertainty in exposure classification and vulnerability approximations. Ideally, local datasets would be used for a city-scale assessment, enabling more accurate damage assessment as well as the attribution of other physical as well as social and economic factors that can significantly affect the impact of flooding or the ability to recover. This approach also allows for a more flexible and meaningful identification of flood risk hot spots and is not necessarily constrained by preconceived or artificial boundaries applied at the start of the assessment.

3.4 EXPOSURE DATA

3.4.1 Baseline Data

Various baseline data are necessary for extraction, analysis, and presentation purposes during a risk assessment. These baseline data may include political, administrative boundaries as well as outlines of relevant features such as watershed boundaries, river networks, permanent waterbodies, and the like.

Information on administrative boundaries, including definitions of various levels (Admin-1, Admin-2, and so on) and agreement about the official boundaries to be used in risk assessments, are essential, especially in circumstances involving contested political boundaries. These baseline data can often be retrieved from existing data portals (such as, for administrative boundaries, the Humanitarian Data Exchange [HDX]).[1]

3.4.2 Buildings and Unbuilt Land

Buildings are usually among the easiest assets to define and the most significant assets at risk, with breakdown by ***occupancy type*** (such as residential, industrial, commercial, governmental buildings, or informal settlements) often identified from OSM. Where building-specific data are not available, alternative methods can be used that apply ***typical*** building uses or types for an area as percentages. For instance, a specific industrial area may have 70 percent industrial, 20 percent commercial, and 10 percent residential use, and these percentages can be used when assigning the building types flooded. This method often requires local information, data, or expert knowledge.

Other relevant building information is the ***structural type***. Buildings can be constructed with different materials such as concrete, masonry, wood, adobe, and so on. The building's structural type is important because this determines how vulnerable it is to floods and also defines the replacement costs.

Typical sources of building information include the following:

- ***Open-source information.*** Often OSM includes polygons of general land use data. OSM does not necessarily have complete or consistent data quality across a city. Cross-checking of the data against recent satellite data is recommended and improvements or corrections made where necessary and feasible. Another open source of land use data is the European Space Agency's Global Land Cover.
- ***Government zoning data.*** Land management and planning roles within local or national government may have usable data that may provide percentages of occupancy.
- ***Property cadastre system.*** The system often only relates to the overall plot but can provide details of land use (and in some instances, value). However, it can also contain sensitive data and therefore be difficult to obtain. It also comes at a cost to obtain, depending on the funding model for the responsible government agency.
- ***Satellite-derived data.*** Various methods have been developed to derive building footprints from satellite imagery (for example, Gavankar and Ghosh 2018). Note that Google Research's Open Buildings Dataset is an open-source product of footprint extraction from satellite imagery, which covers parts of Africa. An initial assessment is that its accuracy estimates are "optimistic," especially relative to OSM (where it is available). Remote-sensing imagery has also been used to define development patterns, including building structure types (for example, Hu et al. 2014).
- ***Local knowledge.*** It may be possible to use crowdsourcing initiatives to define broad land-use or building-type classifications and zones. Targeted crowdsourcing can also help fill in the gaps if OSM is of inconsistent quality across an area or out of date. Input from local specialists (such as quantity surveyors or architects) is generally of great help in classifying structure types and informing realistic replacement costs for these structures.

As for unbuilt land within an urban setting, the impact of flooding can be significant. This land may have many uses, such as urban agriculture, fisheries, or livestock, and may form an important part of the food security chain. Although not specifically built upon, land within the city may also contain assets and belongings of individual households or local communities, such as vehicles, livestock, machinery, or equipment related to small-scale commercial or industrial enterprises. Flood damage to these assets is virtually impossible to quantify directly but should be taken into account.

3.4.3 Population

Flooding affects people in numerous ways, some direct and some indirect. The impacts on individuals or communities are often much less tangible than the direct impacts on buildings and infrastructure, but they are nonetheless just as damaging. Several main factors must be included:

- ***Numbers of people directly affected:*** normally calculated using the residential property count combined with the latest census or equivalent data that provides occupancy numbers or density
- ***Community demographics:*** age, gender, marital status, income or poverty levels, educational attainment, and employment status, for which the type of property and area can provide a useful proxy
- ***Poverty, health, and the recovery capacity:*** important factors to understand to avoid biasing mitigation solutions in ways that help only those who are more able.

Potential datasets for population exposure include the following:

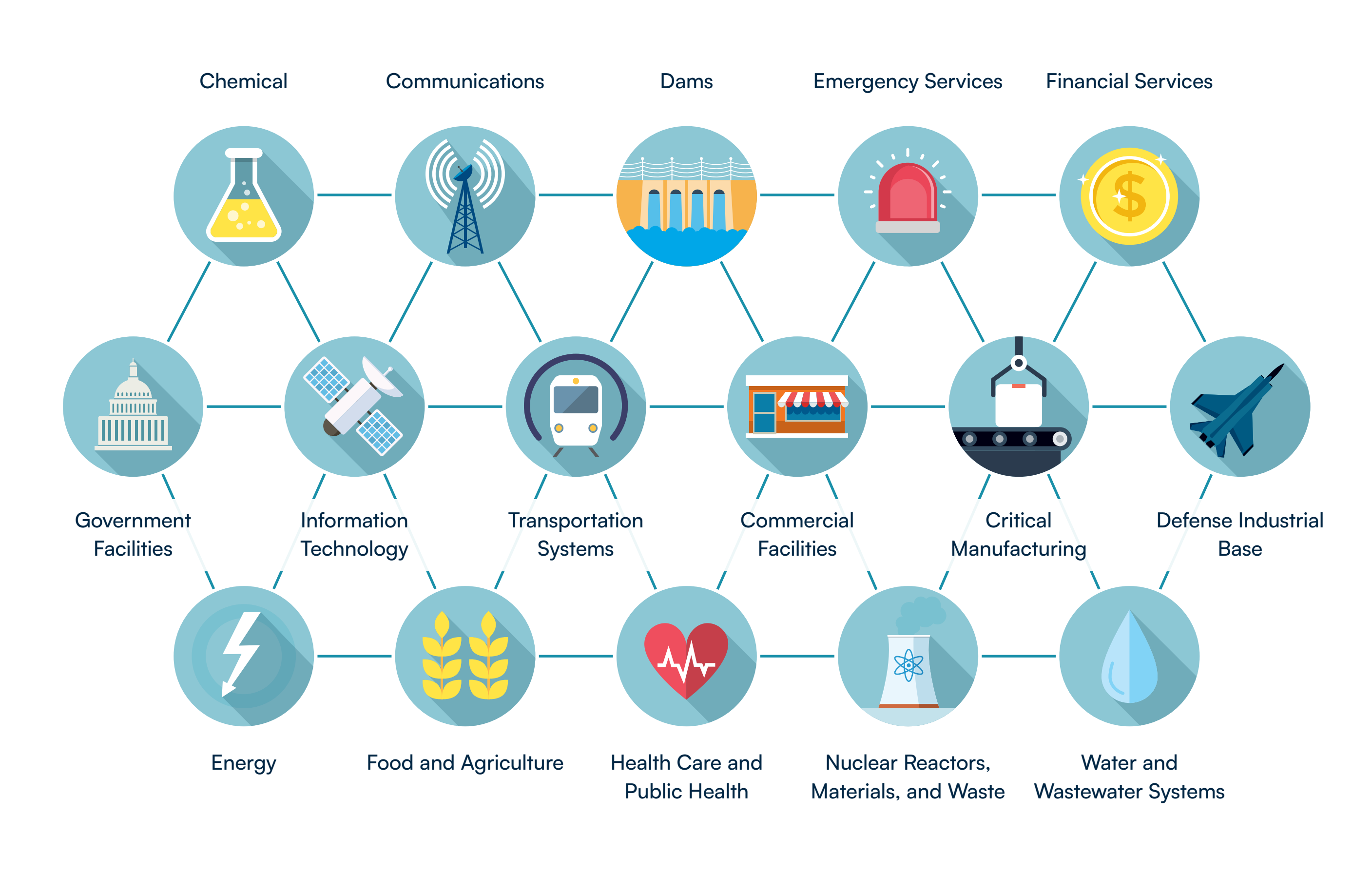
- ***Global estimated data*** such as WorldPop, the Global Human Settlement Layer, and the World Settlement Footprint
- ***Local census data***
- ***Indirect population estimates*** based on per-building or unity occupancy rates, especially useful for high-rise buildings
- ***Specific surveys on vulnerable groups*** such as the elderly, children, disabled, or poor.

Notably, the actual number of people in specific urban neighborhoods at specific moments can be much higher than at other times for a variety of reasons (for example, presence of large markets).

3.4.4 Critical Infrastructure

“Critical infrastructure” is the term used to describe assets, structures, or systems that are essential for maintaining vital societal functions, health, safety, security, economic, or social well-being of people, communities, and government (figure 3.2). Any disruption or damage to these would have a significant impact on a nation as a result of the failure to maintain those functions.

Figure 3.2 Critical Infrastructure Sectors



Source: Adapted from DHS 2016.

Most of these are discrete, geospatially recognizable features such as roads, hospitals, emergency services, dams, electrical substations or power stations, and large factories. Some, however, are less clear, such as communications, information technology, and commercial facilities. If they can be mapped, they should be included in the assessment and, as a minimum, identified as being at risk from flooding or not.

Although it is clearly preferable to identify the specific locations of critical infrastructure, in reality, it is difficult to identify all facilities. Often total numbers (for example, of schools) at the district or subdistrict level can be found from official sources. For the remaining facilities that cannot be accounted for, one potential method for mapping is to statistically distribute these in a gridded dataset based on population data. This may not be ideal for local-level risk analysis, but more suited for a subnational (that is, Admin-1 or Admin-2-level) assessment.

Yet, determining vulnerability for some critical infrastructure is less straightforward, and quantifying the impact of flooding on these types of exposure may not be feasible. It should also be noted that in many countries, certain aspects (such as location) of critical infrastructure will be considered “sensitive data” and may not be available for this type of assessment.

BOX 3.2

Strong Stakeholder Engagement in Indonesia

Engagement of stakeholders in a flood hazard and risk assessment is essential for a variety of reasons. Not only can citizens, government officials, the private sector, and academia provide valuable inputs on the context of floods, but potential interventions can also be identified by understanding the potential for collaboration and action between these actors. The support and action of stakeholders for prioritized interventions is paramount for making interventions sustainable. The urban flood resilience project in three urban environments in Indonesia has engaged with the stakeholders through different inspiring elements.

Rapid urbanization, infrastructure constraints, and regulatory incompliance are key factors increasing the vulnerability of Indonesian cities. The government spends US$300—500 million per year on postdisaster reconstruction. Because climate change and population growth will further exacerbate these issues, chronic flooding in urban environments is an existential threat.

Urban flood risk diagnostics have been developed for three urban environments—Bima, Manado, and Pontianak—consisting of flood risk assessments, urban flood resilience strategies, investment options, environmental and social management considerations, and preliminary cost estimates (World Bank 2020). Specific emphasis has been paid to resilient and inclusive design, with a balance of green, blue, and gray infrastructure.

Intensive stakeholder engagement throughout the entire assignment was adopted, including a close working relationship with local government officials to develop in-house capability and knowledge based on guidance from the Urban Floods Technical Working Group, comprising central government line agencies responsible for urban flood risk management and headed by the Ministry of National Development Planning (BAPPENAS).

The stakeholder engagement strategy comprises four elements:

- **Participatory planning and visioning workshops:** a series of multistakeholder workshops to aim for consensus on the challenges, flood drivers, and opportunities, supported by maps and participatory tools
- **Community-based assessments:** field surveys and community interviews to collect insights and perspectives from citizens
- **Awareness raising materials:** development of materials and visuals to highlight the nature of floods but also to call for action
- **Strategic communication and advocacy:** enhancement of the link and action between local national governments and the national government policies.

Through these elements, the assignment has been successful in engaging numerous stakeholders. These engagements were also accompanied with strong visualizations to support the dialogue.

Participatory Flood Mapping in Indonesia, 2021

Source: © World Bank.

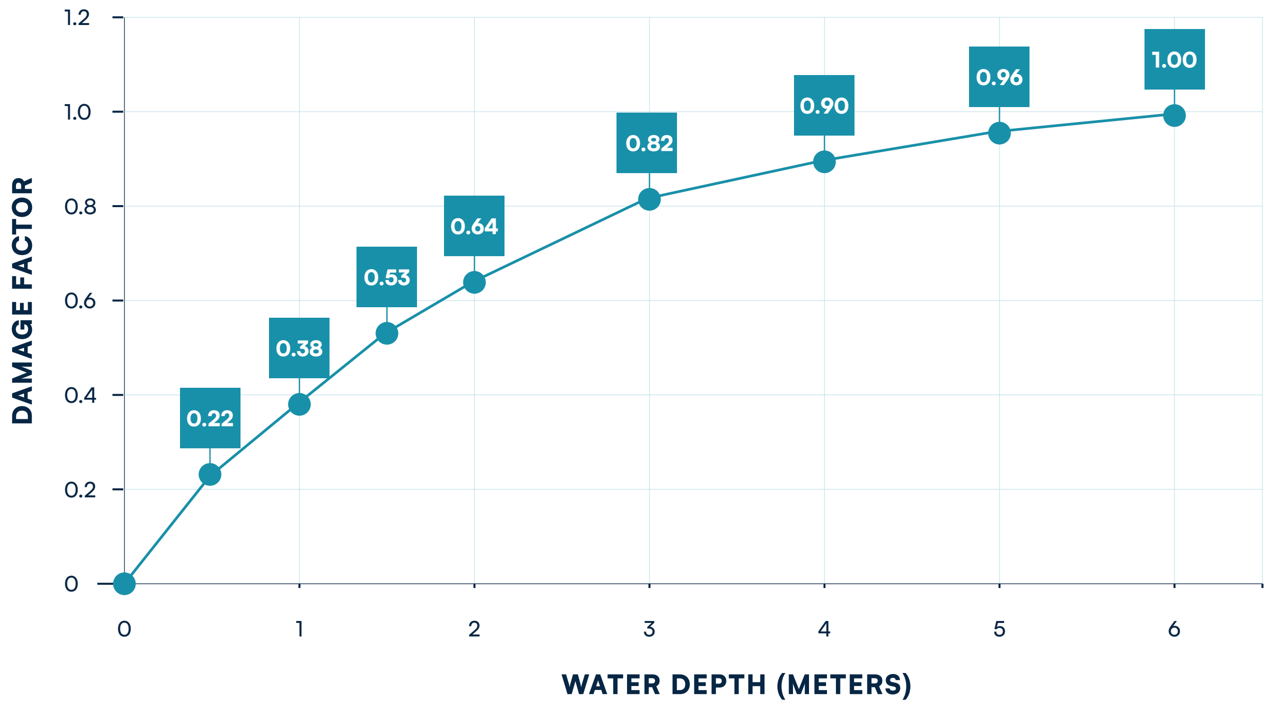
3.5 VULNERABILITY

3.5.1 Direct Damages to Assets

Because actual impact data for all possible events are normally absent, estimating the direct damage to different asset types (buildings, roads, railroads, agricultural land, and so on) for a given flood event is often carried out with the help of asset vulnerability curves and associated maximum damage values. Asset-specific vulnerability curves link the hazard and the exposure to quantify the actual damage to an asset, referred to as a depth-damage function or curve.

The flood hazard is often characterized by the water depth, but sometimes other flood variables are also considered, such as velocity combined with depth or duration. The shape of the curve reflects the kind of building or asset and how susceptible, on average, that type of structure might be to damage from a certain depth of water. The use of generic curves is common where damage is related to a factor or percentage of the building or asset value (or more usually, the value of the maximum damage that could occur to that asset due to that particular hazard—not always the same thing). The use of the curve is simply a multiplication of the factor by the maximum damage value for that asset (figure 3.3).

Figure 3.3 Sample Depth-Damage Curve for Residential Buildings



WATER DEPTH (M)	0	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0
DAMAGE FACTOR	0	0.22	0.38	0.53	0.64	0.82	0.90	0.96	1.00

Note: The "damage factor" is normally expressed as a value from 0 to 1. The table to the right of the graph shows the correlation between the water depth (in meters) and the damage factor for a sample residential building, whose data points yield the building's depth-damage curve.

Defining appropriate maximum damage values for assets in a specific context is important to arrive at realistic flood damage estimates. Maximum damage values (often also referred to as replacement costs) are necessary for the entire range of assets such as buildings but also critical infrastructure such as roads, railroads, and the like. These maximum values are often expressed in US dollars per square meter (USD/m^2) or as an absolute value per building or other asset type, and they will vary significantly by asset type (for example, block of flats, slum dwelling, factory, water sanitation plant, and so on). For line infrastructure such as roads and railroads, these maximum damage values are often provided per unit length but can differ depending on type (for example, paved or unpaved, double or single lane).

There are many useful sources of information for defining maximum damage values, such as local engineering or construction documents; expert knowledge; post disaster need assessments (PDNAs); former projects; and global databases (such as from the European Commission's Joint Research Centre [JRC]). These typically provide maximum damage values for broad categories of assets, which are suitable for a Level 2 assessment.

Verification of information with local experts is often necessary to align the vulnerability curves and maximum damage numbers from global databases with reality. Regarding maximum damage values, a starting point for any damage calculation is to determine what things cost. Price levels, indexation, and means to translate international cost estimates to local context may be helpful. Global datasets are a good starting point, but local verification is essential. Most data are readily available or can be obtained through local contacts, engineering firms or suppliers, and, importantly, expert judgment. There is a large potential for uncertainty within the data, so multiple sources of information will help reduce the likelihood of significant error.

The data below show an extract of actual average cost estimates for Kampala in Uganda and is based on local research and knowledge when compared with the global values taken from the JRC dataset (table 3.2). This demonstrates the importance of carrying out validation using local data whenever possible.

Table 3.2 Replacement or Rebuilding Costs in Kampala, Uganda, 2017

A Residential contents (per building)[a]

ITEMS	COST (US$)
Sofa and chairs	2,000
Refrigerator	800
Cooker	700
Washing machine	700
TV and electrical goods	1,500
Table and chairs	2,500
Carpets and floor coverings	3,000
Bedroom furniture and bedding	1,500
Clothes and personal items	10,000
TOTAL	**22,700**

B Residential construction (per m^2)[a]

BUILDING TYPE	COST (US$/M²)
R1 - Concrete (masonry)	430
R2 - Wooden with corrugated iron roof	75
R3 - Mixed concrete and wood	300
R4 - Wooden buildings on concrete base	150
R5 - Buildings on concrete stilts	695
R6 - Multistory	350

C JRC rebuilding and replacement values [b]

TYPE	COST (US$)
Residential building costs (US$/m²)	340
Residential contents (cost/building)	51,000

Note: US$/m² = US dollars per square meter.

a. Replacement and rebuilding values obtained from local sources in Kampala, Uganda.

b. Replacement and rebuilding values obtained from technical report for Uganda of the European Commission's Joint Research Centre (JRC).

3.5.2 Economic Losses

The most common approach in a Level 2 assessment is estimating the total indirect damage as a fixed percentage of the direct damages. In this way, all indirect damages such as business interruption inside and outside the affected area but also traffic interruption are lumped into one percentage. This assumption is crude but generally acceptable because more-explicit quantification of indirect damages requires large amounts of data (which often are not available) and a depth of analysis usually beyond a Level 2 assessment.

Various studies have provided indications of such percentages based on historical flood events (see, for example, De Bruijn et al. 2015; Hallegatte 2015). A recent study on indirect damage as fraction of direct damages, based on 43 cases, estimated an average of 50 percent (Giupponi 2021). If indirect damage is applied as a fixed percentage, it is always recommended to justify this percentage as well as possible by looking at the specific urban context and acknowledging its similarities and differences with historical cases.

More explicit quantification of indirect damages is sometimes carried out for specific cases such as network analysis for transport infrastructure (for example, Papilloud and Keiler 2021; Rogelis 2016). Flooding on transport links such as road networks can have significant indirect impacts, not only on the individual's ability to travel and go about daily activities but also on the ability of commercial and government bodies to operate. These types of indirect impacts can be assessed if there is sufficient knowledge of activities within the city—gathered by mapping assets, travel routes, and areas affected by flooding—as well as the flood's depth and duration.

In practice, road network data are combined with flood depth and duration data to calculate impacts. For example, the impact on a main trunk road of inundation greater than 0.3 meters for eight hours can be determined through network analysis.

Such an analysis has several key aspects:

- Overlaying flood maps and duration data can define road sections that are subject to flooding.
- Where employment or other areas of high economic activity can be defined, the impact of flooding can be assessed on both access and productivity.
- Network analysis can be carried out to identify the duration of the road closure, alternative routes, and additional mileage or travel time.

- With sufficient granularity of economic data, such as disaggregated gross domestic product (GDP), it is feasible to quantify the economic impact—both on business and industrial output and on individuals or communities.

Using the outputs of the road network analysis, estimates can be derived of the indirect damage due to floods. These can be expressed in various metrics such as monetized damage, travel time, accessibility disruption, and so on. For more details on flood risk analysis of road networks, see the World Bank report, “Flood Risk in Road Networks” (Rogelis 2016), and the examples therein.

3.5.3 Population Impacts

A risk analysis should also assess the vulnerability of the population. These impacts may have various dimensions and degrees of severity and may also vary between different social groups within the communities. The most commonly used parameter to estimate the impact on the population is to calculate the population directly affected by floods. “Directly affected” refers here to the population that lives within the flood extent. Since the degree of impact varies depending on the flood and social characteristics, different classes are often distinguished. Also, a minimum threshold (for example, 10-30 centimeters) is often applied, below which the population is considered unaffected.

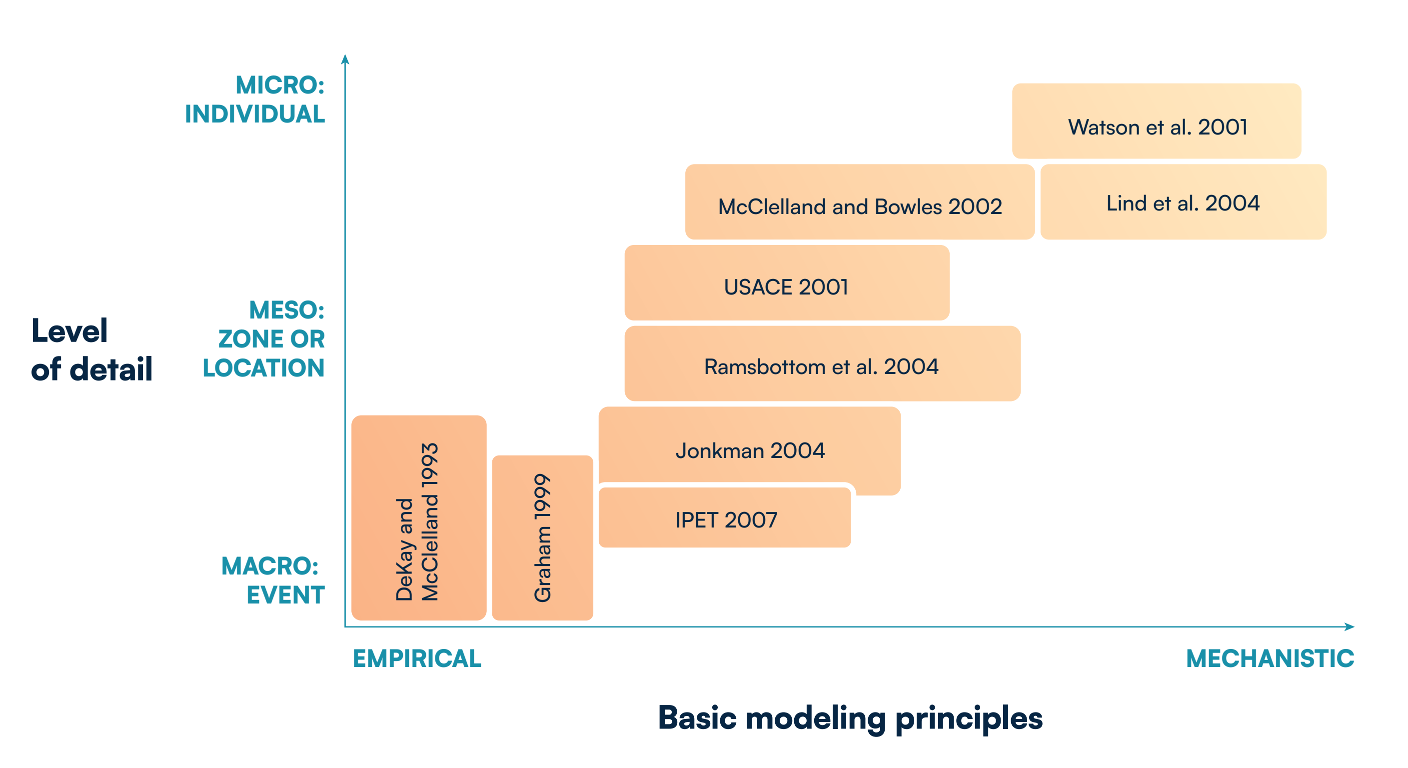
There are several ways to quantify the population directly affected by floods, depending on the data availability. If detailed data exist on the population’s spatial distribution and specific social characteristics (such as gender and poverty), the population maps can be overlaid with flood maps, and the affected population can be quantified for each flood event and presented in various ways. If detailed data are lacking, the affected population may be indirectly estimated using the affected buildings and average household size. Note that these approaches do not account for directly (or indirectly) affected people who (were to) visit the area. In certain urban settings, this can be quite relevant when large daily markets with many visitors are present.

Another less commonly adopted risk indicator for directly affected population is estimating loss of life. (See Jonkman [2007] for an introduction and overview of this topic.) However, some urban floods can give rise to dangerous situations and could cause fatalities, and such an indicator may be useful in a risk assessment. Addressing, estimating, and monetizing loss of life can be a sensitive topic in specific contexts. These sensitivities shall be taken into account before loss of life is considered in a Level 2 assessment.

Mortality models exist with different levels of detail and can be based on different modeling principles (figure 3.4). Mortality can be expressed as a function of flood characteristics such as water depth, velocity, and rise rate (figure 3.5). These vulnerability curves have a high degree of uncertainty; many other factors (for example, temperature, the effectiveness of warning, and arrival time) may play a role, and thus these estimates should be used with great caution. Potential loss of life due to flooding can also be empirically related to the overall number of people exposed to a given flood event.

Regressions based on major coastal flood events in recent history may be used with caution where there is a significant likelihood of conditions that would be dangerous to life. Most flood-related fatalities globally occur while people are away from their homes and usually are trying to reach safety and travel through floodwater (figure 3.6).

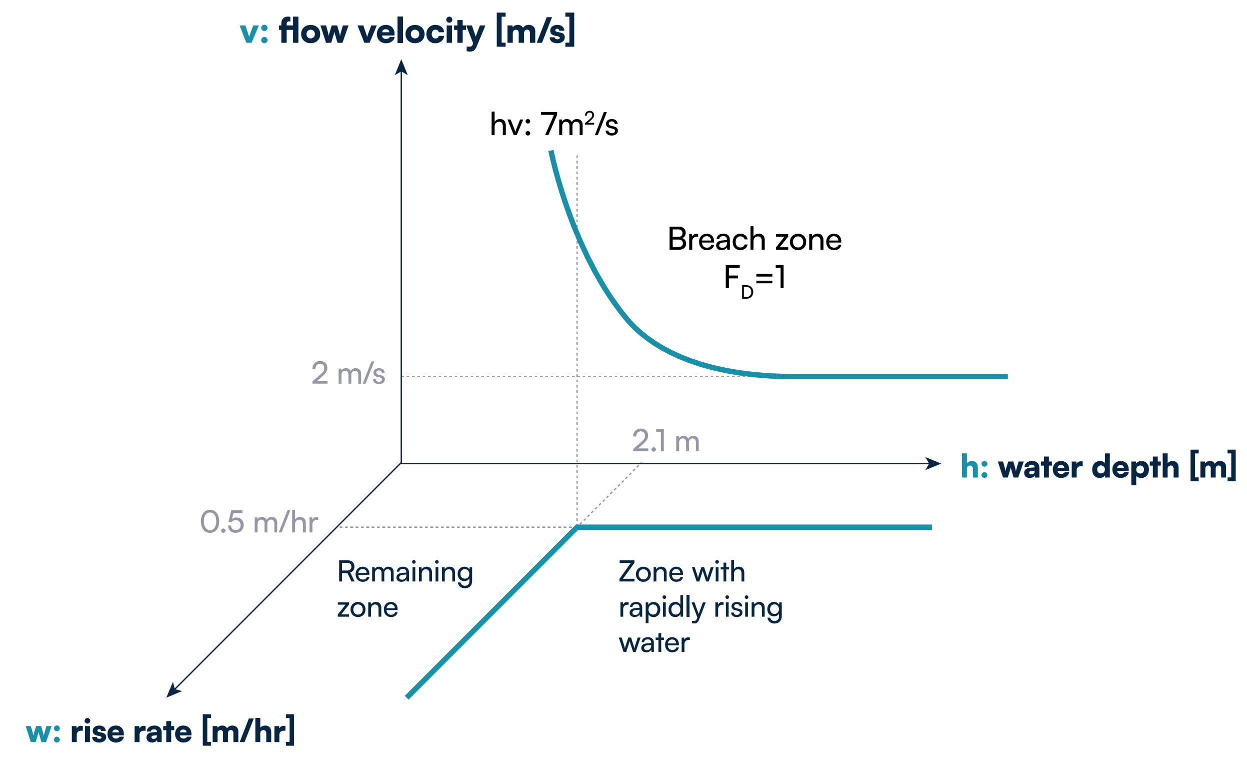
Figure 3.4 Different Models for Loss of Life from Flooding, by Level of Detail and Modeling Principles



Source: Johnstone et al. 2005.

Note: Each citation represents a different model for loss of life. For more detail, see the reference list entries for these citations.

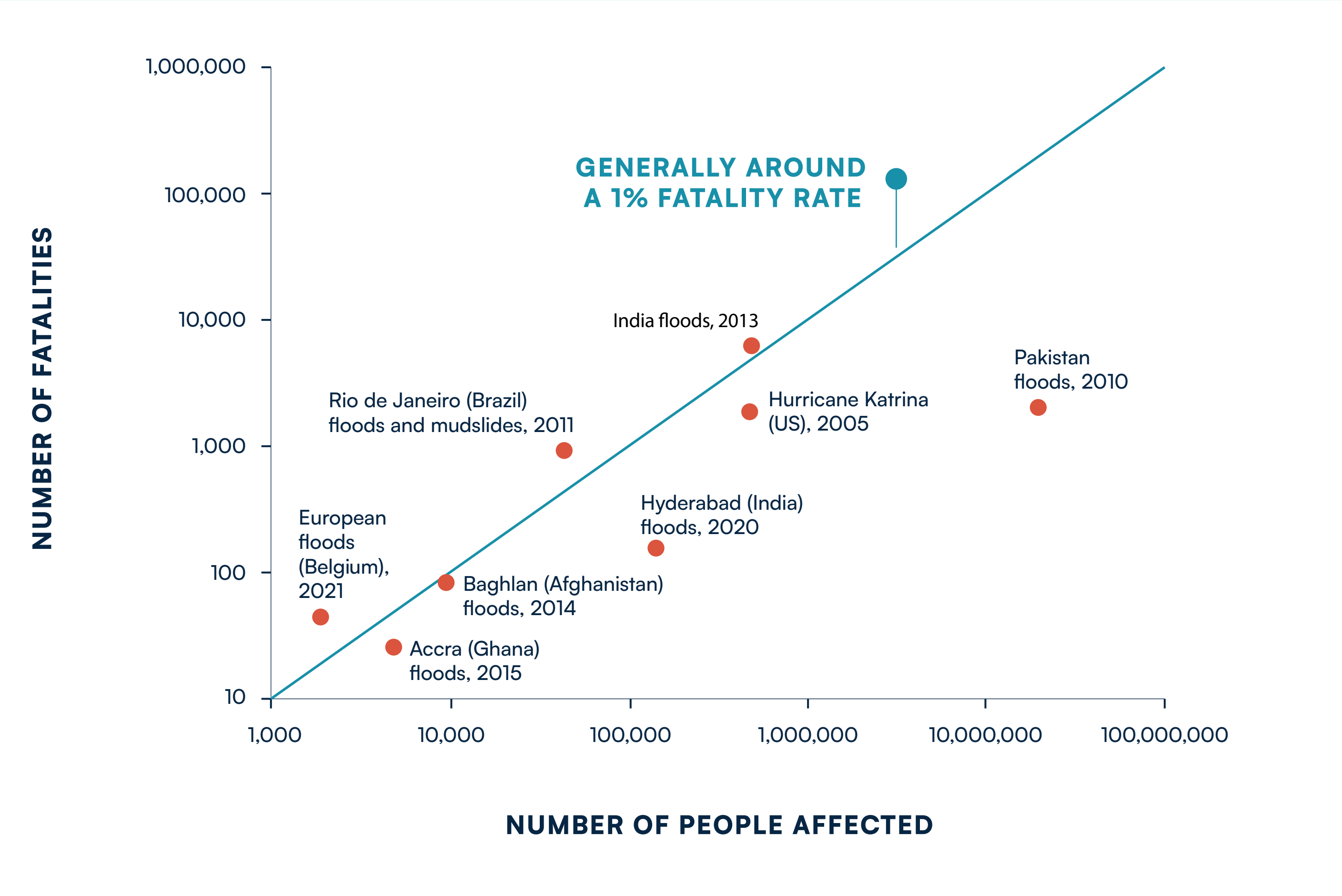
Figure 3.5 Example of Mortality Function as Function of Water Depth, Rise Rate, and Flow Velocity



Source: Jonkman 2007.

Note: FD = mortality (or fatality) probability; h = water depth; m = meters; m/hr = meters per hour; m/s = meters per second; v = velocity.

Figure 3.6 Mortality Rates from Eight Recent Floods in Selected Countries, 2005-21



Source: Jonkman 2007, using data from the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED).

Note: Graph displays data from eight floods, a selected sample of large-scale flood events.

3.6 FLOOD RISK SIMULATION SCENARIOS

3.6.1 Role of Event Impacts

Different scales of economic and social impacts occur for different events (see typical examples in figure 3.7). During a frequent, typically annual event, some damage and disruption may occur but with little threat to life. During extreme events, which only happen very rarely, communities may experience serious consequences with heavy losses, both economic and social. For large events, data collection and analysis are generally carried out to provide loss and damage estimates and inform rebuilding and recovery activities. While this information will be event-specific, it can provide useful indicative values for validation of impacts and damage calculations for simulated or potential real events elsewhere.

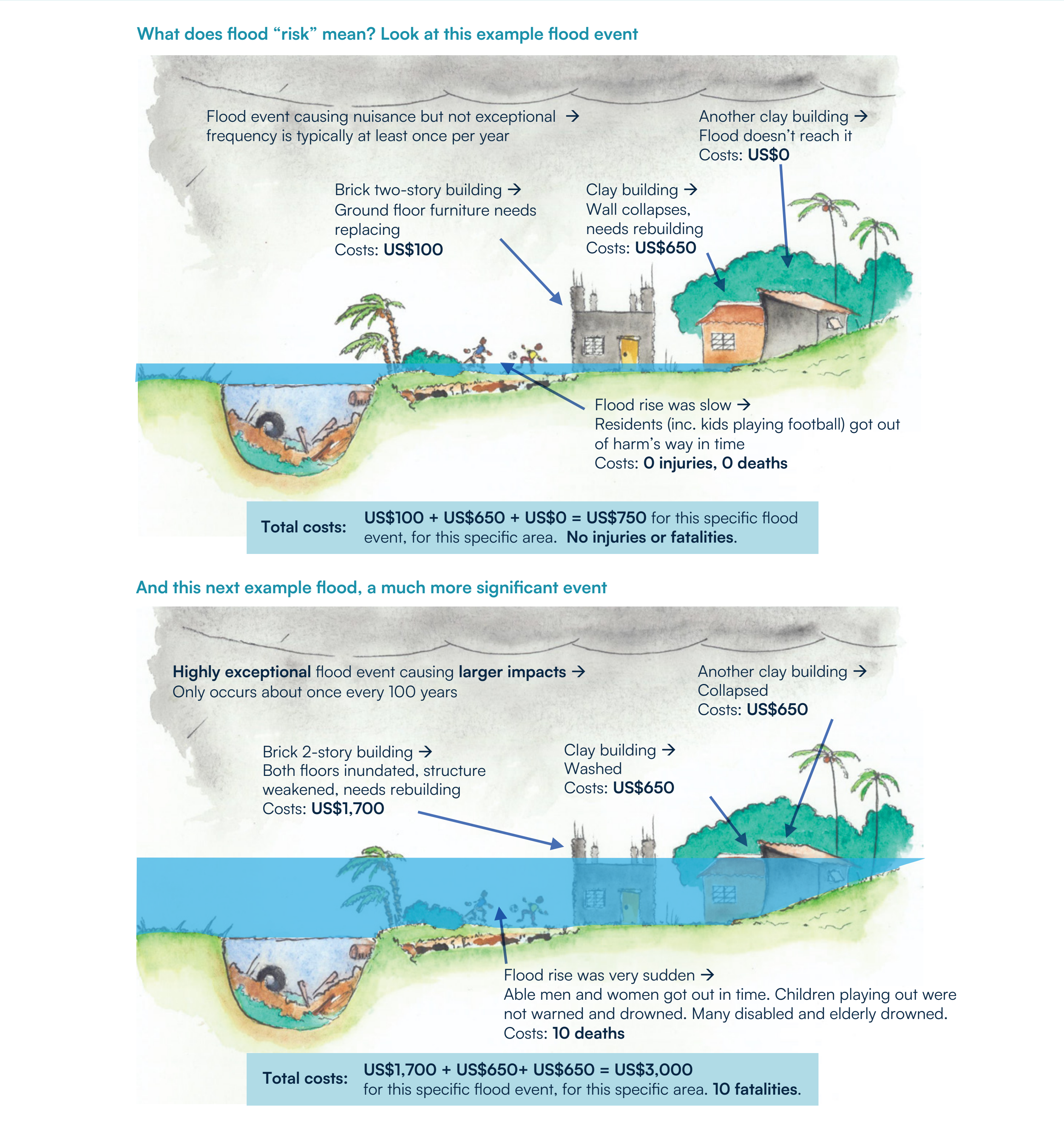
Global databases of data from past flood events also can be useful in this respect. See, for example, the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED) and the United Nations open-source tool, DesInventar.

Quantifying the impact from a flood during an event normally involves several key parameters:

- Depth and extent of the flood
- Occasionally the velocity and speed of onset and the duration of inundation
- Type of water (for example, sea, heavily polluted, high debris, or sediment load)
- Type of exposure and an area's vulnerability to flooding
- Coping or recovery capacity of households.

A common parameter often used to classify the intensity or danger of the flood hazard for a specific event is the flood hazard rating (for example, Defra 2008). This criterion combines the depth, velocity, and debris into one single parameter to quickly assess the flood hazard intensity in the area of interest. Especially for flash floods and dam break assessments with high velocities, this flood hazard rating can provide good insight into the spatial variation of the danger of a specific flood event. Such an event risk map can be a useful tool in a Level 2 assignment to provide an initial view of the spatial distribution of the danger based on the outputs from the flood hazard modeling.

Figure 3.7 Flood Events of Different Scales of Impacts



Flood risk is the integration of the impacts across all possible events, ranging from frequent, low-impact scenarios to infrequent, high-impact scenarios. Flood risk should not be confused with the impacts of individual events. The impacts for specific events are sometimes also referred to as "event risk" to make this distinction clear. In the determination of flood risk, the impact of specific events are intermediate results that feed into the risk calculations. The impacts of events are weighted by the probability of the various events. In this way, all events are accounted for in a risk calculation.

3.6.2 Quantification and Mapping of Risk Metrics

The results of the flood hazard simulations discussed in chapter 2 are the starting point of the risk quantification. These flood hazard simulations cover both existing and future conditions for a range of flood events with different return periods. The future scenarios also include uncertainties related to climate change, urban growth, and other relevant factors (for example, subsidence). The future risk scenarios should be based on the same set of scenarios for urban growth and land use changes.

The risk simulations in a Level 2 assessment with a set of events first quantify the impacts to population and assets using these flood hazard events and then convert these into risk estimates by integration across frequencies. For example, the economic flood risk at a location or area is thus calculated as the integration of all the damages and losses over a range of different return period flood events (probabilities).

Commonly used risk metrics for direct and indirect damages are the expected annual damage (EAD) or annual average loss (AAL). In a similar way, the "annual affected population" is often used. A solid understanding and communication of these risk parameters is important for the stakeholders involved. It is important to realize that these metrics

- Are long-term average values recurring each year for the current situation;
- Can be largely exceeded depending on the severity of an event;
- May increase or decrease in the future because of climate change, socioeconomic changes, or both; and

- Can be managed through structural and nonstructural interventions by either influencing the hazard probability (for example, by drainage works); exposure (for example, better zoning); or vulnerability (for example, improving building codes).

The expected annual population affected can be an important indicator of which areas within an urban environment should be prioritized for interventions. The EAD is a key ingredient in a cost-benefit analysis for economic justification of any kind of intervention to reduce the risk. This will be further addressed in chapter 4.

Special attention should be paid to how to map these and other risk indicators for communication purposes to the stakeholders. As in flood hazard maps, aspects like specific contents, scale, and use of color are applicable here as well. Because flood risk is an integration of event impacts and probabilities, the wider audience's interpretation of risk maps is generally not straightforward. It may also help to generate a set of maps with impacts for individual events, since stakeholders can generally relate more easily to these based on their own experiences.

Also, it is important to think about what level of detail is presented in view of the accuracy of the results in such an assignment. The results of a Level 2 assignment are typically presented for subareas within an urban context or (sub)catchment scales. Normalizing the results based on the area size may then be necessary to have a fair comparison of the level of risk in the various areas.

3.7 RISK CALIBRATION AND VERIFICATION

Flood damage and risk modeling have many uncertainties due to various factors: limited data, model resolution, and multiple models (hazard, exposure, and vulnerability). Understanding sources and causes of these uncertainties at all stages of the assessment is essential. Moreover, calibration and verification against existing data and knowledge are key steps to arriving at realistic results. Potential data sources for calibration and verification of the hazard and risk results are historical events (as documented in PDNAs); global loss databases such as EM-DAT; the

World Bank's Climate Change Knowledge Portal; and local records, media reports, and expert judgment. Note that PDNAs and other official databases often report only severe events, whereas more information on more regular events can also be found in media reports.

Calibration is the process of using ***real-life*** data during the model development process to select the parameter values and methods to best fit the calibration events. This is an important aspect of hydrological, hydraulic, and risk modeling procedures; it requires a systematic approach and depends on real-life data or information. The calibration process should be carried out at all stages to ensure that the intermediate and final results are as accurate as possible and not a function of a lucky combination of incorrect modeling steps. This principle applies to the various stages of the process, including hydrology, hydraulics, exposure, and vulnerability assumptions as well as attempts to quantify less-tangible aspects of flood impacts. Different parameters can be used in the process of calibration, such as the roughness coefficient in hazard modeling and damage values and vulnerability relationships in the risk modeling.

Verification is the process of comparing the results of the calibrated model against a set of ***real-life*** results at each stage of the modeling process—that is, of hazard modeling, exposure mapping, and vulnerability assessment. It is essential that a different set of real-life results are used for verification, and it is good practice, where data allow, to randomly split the real-life event data into two equal sets—one for calibration and the other for verification. In practice, sufficient data are seldom available to allow this approach, and calibration is done using any and all data available and verified using local knowledge and experience and a commonsense review of the final results.

A practical example of flood risk calibration is provided in Kazi et al. (2022). The coastline of Bangladesh is vulnerable to cyclones, and the risk of cyclone flooding has been assessed for the entire coastal zone with a current population of 48 million people. The risk model provides estimates of damage to assets such as housing, infrastructure, and economic activities such as agriculture. The PDNA of a recent severe cyclone in the region (Cyclone Sidr, 2007) was then used to evaluate how the modeled damages compared with these values. Although the initial risk modeling estimate was within reasonable limits given all uncertainties involved, a correction factor has been applied to align the modeling results better with the damage numbers in reality.

In general, the following may be useful to consider in this process of calibration and verification:

Reports with damage numbers of severe events:	Maximize the use of existing damage and loss reports and databases (for example, PDNAs and EM-DAT). Because these are historical events, the numbers given may need to be adjusted to reflect present-day values. Do the risk modeling numbers align with evaluated historical events of a similar intensity or extent? If not, can the differences be explained?
Sensibility:	Does expert judgment, experience, and local knowledge confirm that the results are sensible and reflect what might be expected from an event of a given scale in a given location? If they are not reasonably close to what is expected, why not?
GDP:	What percentage of GDP is being affected? Is that percentage considered to be realistic, and does it align with flood risk data for other similar settings? And if not, is there a good explanation for this particular situation?
Media reports:	What are the impacts of frequent—that is, every rainy season—events? Does the modeling of very frequent events result in (almost) zero damage, as would be expected?

As with the hazard assessment, an additional sensitivity analysis should be carried out for the risk assessment stage. The same principles apply, in that the analysis investigates the potential error associated with the key parameters or input variables of the analysis by systematically varying each in turn over a range of possible values. For the risk analysis, this may include asset types or values as well as the vulnerability curves for different exposure types. The shape of the vulnerability curve (or starting point) can significantly affect flood damage values—which are often based on empirical relationships derived from a small sample of exposure types (such as building types) and are usually based on an average, or a typical typology over a given area, and therefore can be very uncertain. Even a simple check against assumptions, such as the average number of occupants in a given type of dwelling, may show significant variations in overall “population affected” figures. Understanding how this uncertainty can affect the final results is important to the ability to use the risk assessment results with confidence.

Level 2 project experiences highlight the difficulty of risk quantification in these assignments for lack of data. But among other things, the flood risk metrics are used to prioritize and justify the locations and level of investments in these areas. If the level of risk is far overestimated, this might potentially lead to wrong investment strategies and decisions. Hence, it is important that the risk quantification be verified at least qualitatively to achieve credible information for selecting and prioritizing intervention options.

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ENDNOTES

1 HDX is an open-source platform for sharing data across crises and organizations. Launched in July 2014, is managed by Center for Humanitarian Data of the United Nations Office for the Coordination of Humanitarian Affairs (OCHA). For more information, see the HDX website: https://data.humdata.org/.

CHAPTER

4

EVALUATION OF INFRASTRUCTURE INTERVENTIONS

Table of Contents ←

4.1 INTRODUCTION

Many cities face significant urban flood risk, hampering the economic growth of these centers and the well-being of their citizens. These risks are caused by many factors but often include a lack of investments in all types of infrastructure (gray, green, and blue); limited funding for maintenance; absence of land use planning and enforcement; and poor governance. These risks are exacerbated by climate change, which will further stress the malfunctioning systems.

Such issues are often more pronounced in low- and middle-income countries because of strong urban growth over a short period, resulting in an "adaptation deficit." As Noble et al. (2014, 839) frame the situation for the Intergovernmental Panel on Climate Change, this deficit is "the gap between the current state of the system and a state that would minimize adverse impacts from existing climate conditions and variability." To overcome this adaptation deficit, evaluating and prioritizing interventions is a key step, which is often part of a Level 2 assessment. These interventions are generally then taken forward in more detailed studies to prepare for implementation.

Evaluation and prioritization of interventions requires analysis of the appropriateness of specific interventions to reduce the risk of flooding for an urban environment. Potential solutions to mitigate flood risk are typically multiple, and a portfolio of approaches is often the end result. For example, a combination of embankments to protect high-density urban zones in combination with early warning and shelters for low-density areas and zoning for areas that have not yet been developed may be the result of this evaluation. In a Level 2 analysis, many options must therefore be screened in an efficient but also robust way, and special care should be given to integrating the flood risk analysis and hazard mapping with urban planning and development.

The appropriateness of interventions depends on a wide variety of factors, but cost-effectiveness of the investments, the environmental and social impacts, and sustainability after implementation (for example, sufficient resources and capacity for operation and maintenance) are important elements. Consideration of the existing and future uncertainties is essential throughout this process of evaluating possible interventions to arrive at robust options.

The following questions are relevant to the evaluation of interventions:

What types of interventions are possible, and how to select the most relevant ones?

Can the proposed interventions be modeled in some way to allow quantification of their effectiveness?

What are possible future climate and socioeconomic scenarios that should be applied to test the future effectiveness and robustness of the interventions?

What are the benefits and costs of these interventions, and are there secondary (or multiple) benefits and costs that should be considered?

What are the environmental and social impacts?

Throughout the entire process of selection and evaluation of flood risk management interventions, it is important to recognize that the potential success of any intervention is strongly interlinked with a well-functioning institutional setup dealing with urban flood risk management and more broadly with the urban planning process. In many situations, several agencies are involved with overlapping mandates, resulting in uncoordinated actions and confusion. Getting a clear picture of this institutional setup for the specific urban context is therefore critical. It is also important to understand how potential interventions would fit within these institutional arrangements and associated planning processes. It may even be necessary to consider whether further institutional realignment or changes may be necessary to ensure that any interventions successfully implemented are sustainable in the long term.

Stakeholder involvement is therefore crucial during this phase. Stakeholders can offer unique viewpoints on how interventions could benefit their community, and the inclusion of all relevant stakeholders increases the likelihood of equitable outcomes and benefits for all parties (Rözer et al. 2021). Stakeholders can also help to identify multipurpose solutions. For instance, interventions for urban flood risk reduction can often address other specific needs in a city environment such as improving water supply, increasing biodiversity and restoration of urban ecosystems, expansion of recreation zones, and helping address urban heat island effects.

A good example in this context is the rehabilitation of the Rio Chiveve Park in Beira, Mozambique (CES, Salzgitter, and Inros Lackner 2020). This project started originally as a conventional drainage project but has resulted in not only an improved drainage situation but also a healthy urban park environment with increased biodiversity through the restoration of the river ecosystem. This example highlights how a drainage intervention can offer more than flood risk mitigation and catalyze livability enhancement of the urban environment.

4.2 IDENTIFICATION OF INTERVENTIONS

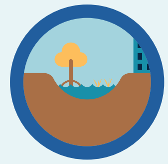
A wide range of interventions can often be defined to reduce the risk of urban flooding. Clarity about the types and scales of possible interventions to be considered in the urban flood risk assessment is essential for a good definition of the scope of the project. The appropriateness of these interventions for a specific situation depends on the physical and institutional characteristics of the situation. Various classifications exist to distinguish different types and spatial scales of interventions. A classification can help stakeholders to understand the wide range of interventions; it also supports a transparent, informed selection process of appropriate measures to be further evaluated.

4.2.1 Classification of Structural and Nonstructural Interventions

Gray, green, and blue structural measures. A useful way to distinguish between types of interventions is to classify them as structural or nonstructural measures (figure 4.1). These two types of measures could be further subdivided into different groups for clarity. For example, structural measures are often classified as gray, green, and blue measures:

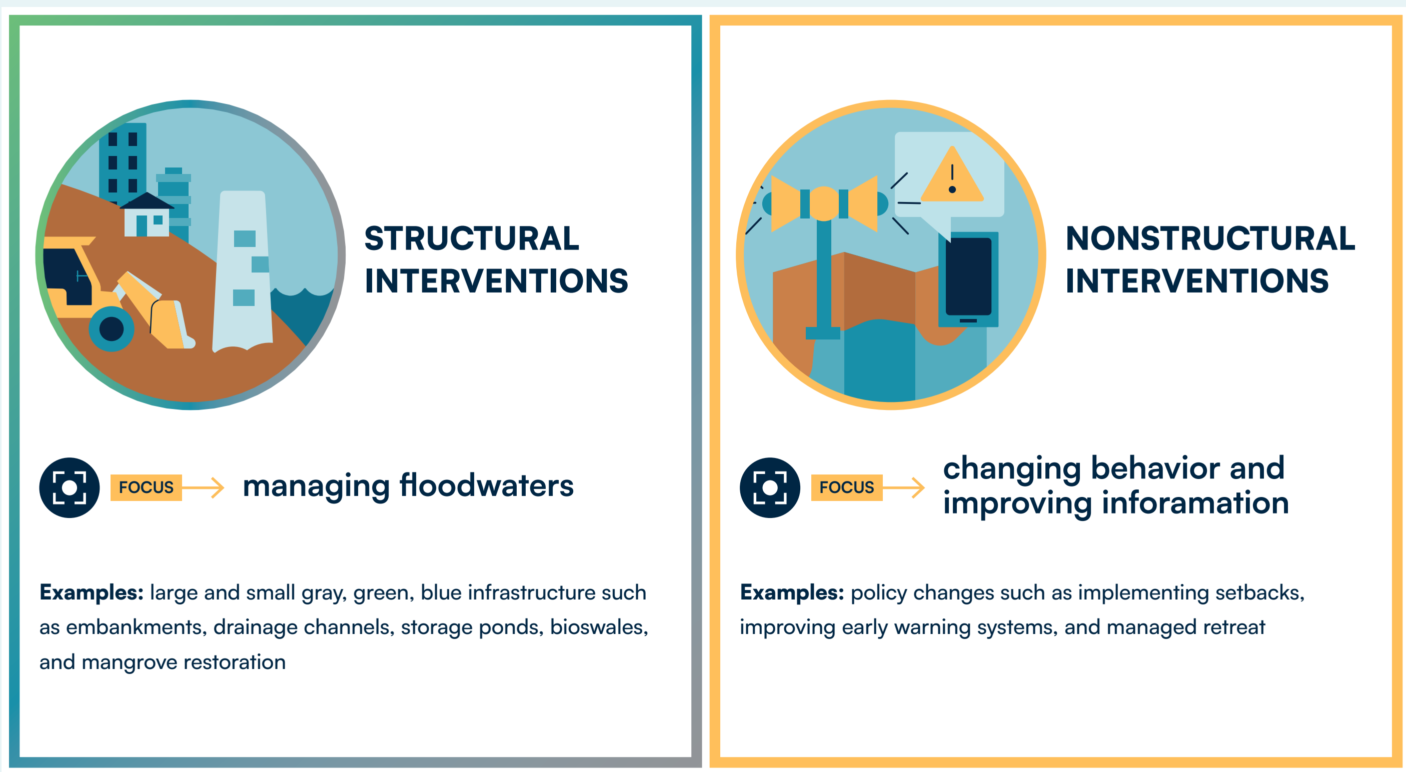
Gray measures
are those that will hold back or divert water, consisting largely of hard materials like concrete, rock, or steel (such as culverts, lined canals, pump stations, and outlet sluices).

Green measures
are those that slow the water down or help absorb it, such as mangrove regeneration or installation of bioswales, open green spaces, and urban forests.



Blue measures
are those that allow flood storage as open water, such as retention basins, by restoring former wetlands or floodplain landscaping that allows space for floodwater without causing damage.

Figure 4.1 Structural versus Nonstructural Interventions



Green and blue measures are often lumped together as “nature-based solutions” (NbS), which refers to “actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges . . . effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al. 2016, xii). Compared with traditional gray infrastructure, NbS for urban drainage generally come with multiple benefits including not only flood risk mitigation but also potential contributions to restoring biodiversity, improving human health, and creating opportunities for recreation, among others. A useful reference for identification of potential NbS and their costs and benefits in an urban environment is the “Catalogue of Nature-Based Solutions for Urban Resilience” (World Bank 2021).

Nonstructural classifications. Nonstructural measures can typically be divided into

- ***Land use planning and zoning*** such as building codes, zoning with restricted or prescribed uses, and in some extreme cases, managed retreat where land is allowed to become unusable for any form of development or urban use;
- ***Flood forecasting, early warning, and emergency response***, which provide response agencies as well as the public with actionable information in a timely and appropriate way that will reduce the impact of flooding and will include raising awareness, response planning, and evacuation; and
- ***Postdisaster recovery*** such as adaptive social protection, cash transfers, or insurance schemes.

Both structural and nonstructural measures have strong links with urban planning since these interventions (if structural) need space or require enforcement (for example, of zoning laws). Hence, evaluation of the measures requires the integration of urban planning with the flood risk analysis.

In practice, however, the exact delineation between the various types of structural and nonstructural interventions is not always easy, and often the best approach is a combination of measures. This can make decision-making and investment option selection complex, and a simple cost-benefit approach may need to be supported by multicriteria analysis.

4.2.2 Classification by Spatial Scale

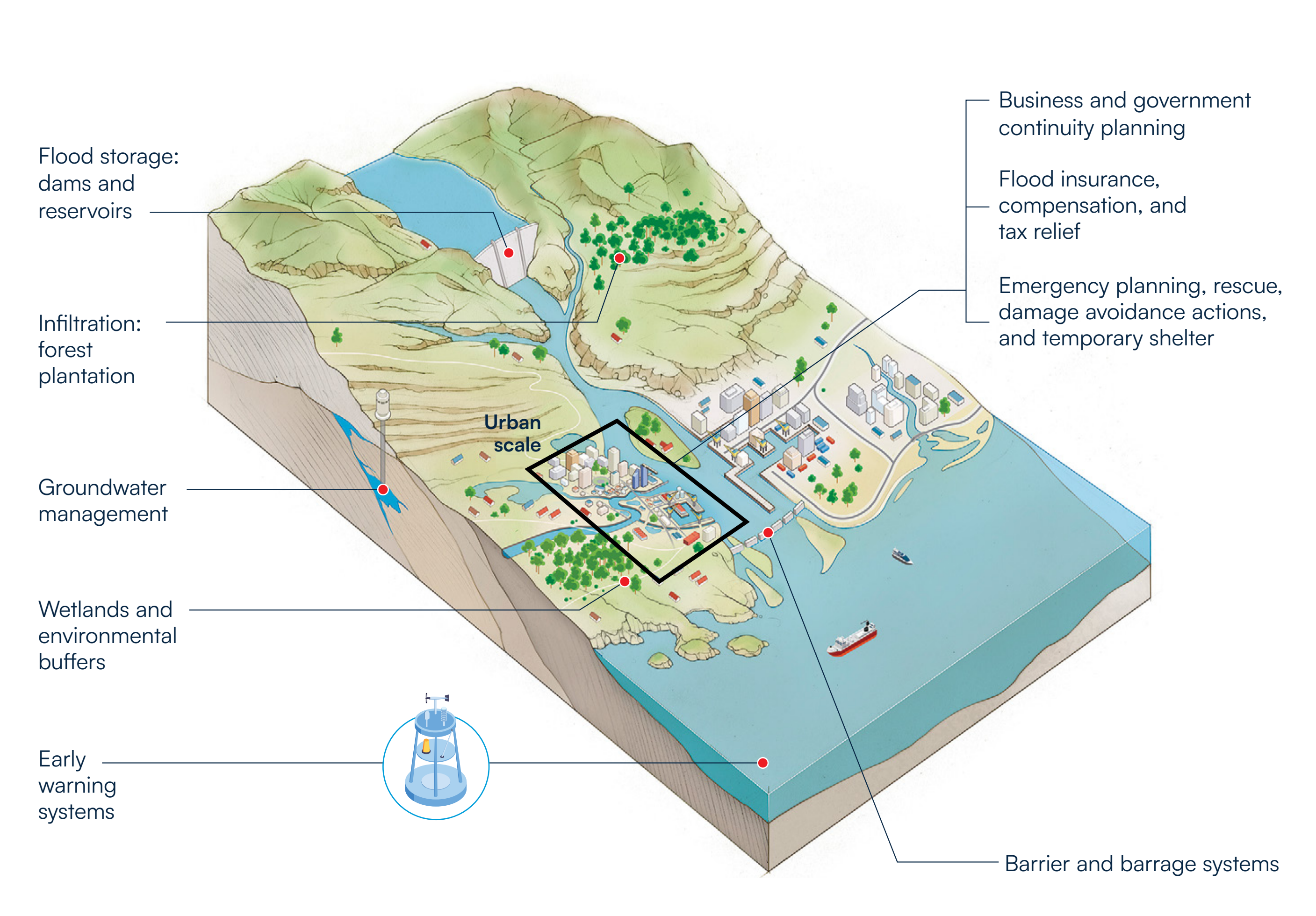
Another useful way to distinguish interventions is by looking at the spatial scale of the interventions:

- Catchment scale
- City scale
- Neighborhood scale
- Building scale.

Figures 4.2 and 4.3 illustrate two scale levels—catchment and urban scale—with typical possible structural and nonstructural interventions at these scale levels to manage flood risk. Catchment-scale solutions relevant for urban flood risk may be the construction of upstream reservoirs or better land use planning to reduce and delay runoff from the upstream catchment (figure 4.2). Examples of city-scale measures are early warning and land use zoning within the city perimeter or building embankments to reduce the probability of flooding from the river or the sea (figure 4.3). Neighborhood-level measures include improvement of local drainage or delay of runoff through green roofs or better infiltration. Last but not least, buildings could be raised, or floodproofing of buildings can be considered.

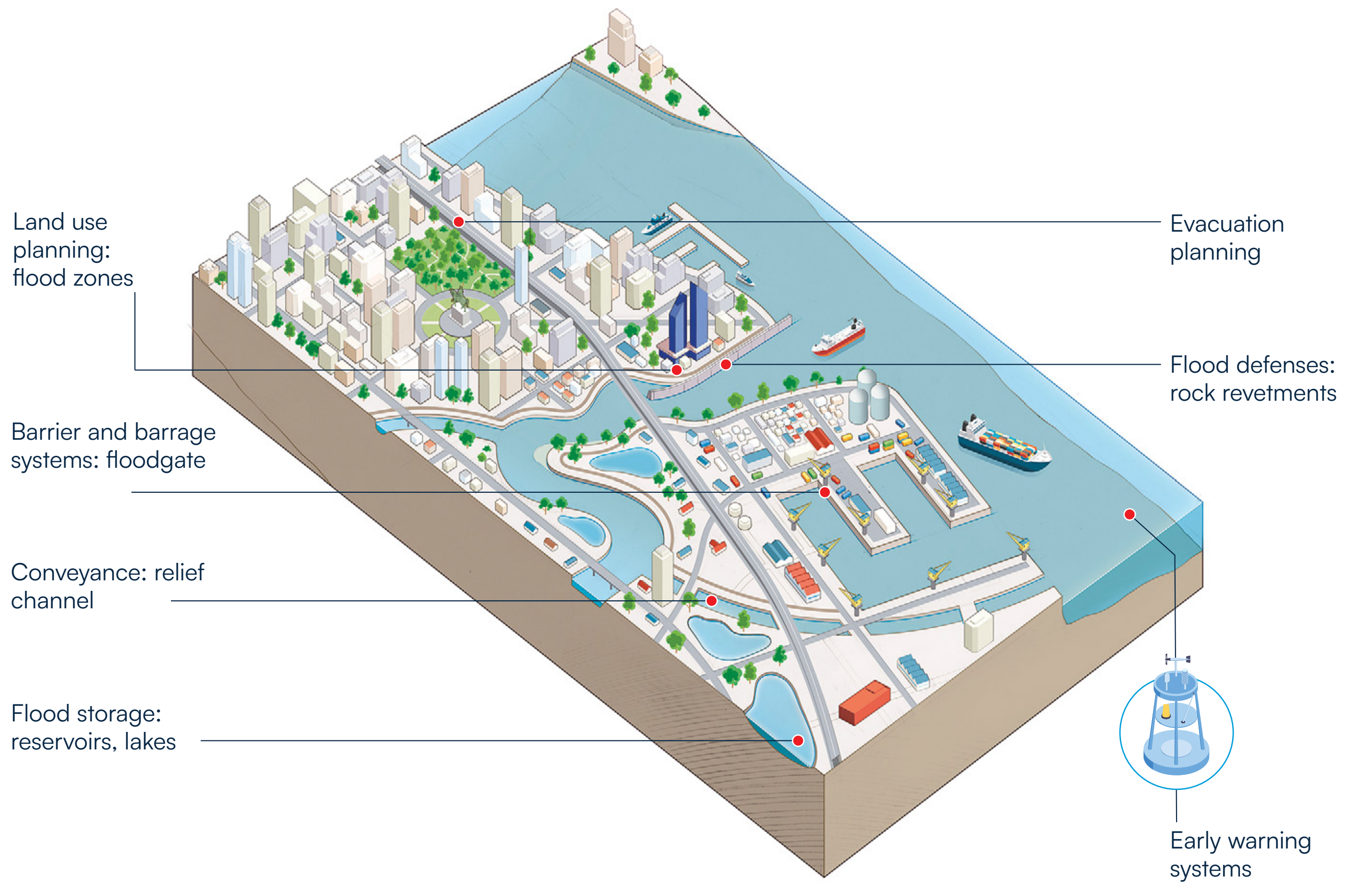
Spatial scales and interventions can overlap, such as in the case of an early warning system that could be implemented at the catchment level but may also provide specific information at the neighborhood level. Hence, the classification should be considered as a tool to help guide discussions with the stakeholders, and a clear and concise definition of each intervention remains important.

Figure 4.2 Catchment-Scale Interventions



Source: Jha, Bloch, and Lomond 2012. ©World Bank.

Figure 4.3 Urban-Scale Interventions



Source: Jha, Bloch, and Lomond 2012. © World Bank.

The examples at different spatial scales (figures 4.2 and 4.3) highlight the fact that many different types of interventions can reduce flood risk, but if they are not well defined in terms of both spatial coverage and scale, they could easily lead to significant scope creep of the study and require far more detail than the Level 2 urban flood risk assessment would normally provide. For example, flood forecasting and early warning systems are known to be effective interventions. However, they can be difficult to represent within a flood risk assessment framework and may require quite sophisticated analysis to quantify the benefits as accurately as, say, building a flood relief scheme. In some instances, it may be adequate to simply acknowledge flood forecasting and early warning systems as important nonstructural measures to reduce flood risk; they could be cited in flood risk management interventions and identified as ongoing or future flood forecasting and early warning studies that will be referenced.

4.3 SELECTION OF INTERVENTIONS

In a Level 2 assessment, the initial screening and selection of interventions with potential for the urban context is generally done based on qualitative considerations and indicators. Engaging stakeholders but also leveraging expert knowledge in this stage is important to ensure that all possible interventions are evaluated and carefully considered.

A shared vision among stakeholders generated at the conceptual level is important at the initial stage of identification and selection of potential interventions. This vision may include a range of possible ways to manage the risk from flooding now and in the future; ideas of what an acceptable level of risk would be; how to address residual risks; whether there is a potential opportunity for resolving other urban needs through a multipurpose solution; and how the proposed interventions fit into the institutional setup. This vision will need to be based on a thorough understanding of the functioning of the urban environment with specific emphasis on the magnitude and distribution of flood hazard and risk both now and in the future.

4.3.1 Defining the Indicators

Indicators are the quantifiable outcomes of the proposed intervention or investment if it were to be successfully implemented. These outcomes (or indicators) would be directly measurable or countable once the intervention was in place (given sufficient time to monitor how it performs and gather the necessary data). However, to compare and select the optimal intervention from a long list of possible interventions before they are implemented, the indicators must be assessed in as accurate and robust a way as reasonably practical given the data and detail of the Level 2 assessment. This normally requires some form of modeling or geographic information system (GIS) analytical processing to quantify these indicators.

These indicators must be sensibly defined to genuinely reflect the benefits (either direct or indirect and including multiple or cumulative benefits) that are likely to accrue as a direct result of the interventions. A well-selected, well-enumerated framework of indicators can help support a transparent and evidence-based decision-making process. Such a framework must be developed on a case-by-case basis, reflecting not only the primary aims of the interventions but also the local stakeholders' secondary preferences and needs.

These indicators generally include technical, economical, ecological, and social aspects. Typical indicators may include the intervention's technical complexity and adaptability (sometimes referred to as "achievability"); the total costs, benefits, and benefit-cost ratio; the reduction in number of the affected population (specified for different social, age, and gender groups); the amount of land acquisition and resettlement; changes in biodiversity, water conservation and supply; changes in recreation opportunities; and improved access of transportation routes, among others. A key indicator for any flood risk management intervention is its level of risk reduction. For structural interventions, this is generally governed by the adopted "protection level" or "design standard," often expressed in terms of an event return period.

Table 4.1 lists return periods for different types of flood protection infrastructure (modified after Ponce 2008). For densely populated urban environments, the commonly adopted return period to protect against coastal and riverine floods across the world ranges from 100 to 10,000 years. Urban drainage systems that provide flood protection against local rainfall events are generally designed for event return periods from 5 to 100 years. It is common engineering practice to apply these return periods for the situation at the end of the lifetime of the infrastructure (for example, after 50 years), through which climate change effects (such as increased rainfall, or higher sea levels) are appropriately accounted for in the infrastructure design.

Table 4.1 Indicative Values for Selection of Return Periods of Structural Interventions

PURPOSE OF INTERVENTION	TYPE OF PROJECT OR FEATURE	RETURN PERIOD (YEARS)
Infrastructure for coastal and river events	Embankments (low risk with low concentration of population)	10—25
	Embankments (medium risk)	25—100
	Embankments (high risk with dense population)	100—10,000
	Floodplain development (low risk)	25—50
	Floodplain development (high risk)	100
Infrastructure for local pluvial events	Urban drainage (low risk: up to 100 ha)	2—10
	Urban drainage (medium risk: 100—1,000 ha)	10—50
	Urban drainage (more than 1,000 ha)	50—100
Other infrastructure	Bridge design (piers)	100—500
	Principal spillways (dams) Emergency spillways	25—100 100—10,000 (PMP)
	Minor road Major roads	5—10 10—50

Source: Modified after Ponce 2008.

Note: ha = hectares; PMP = probable maximum precipitation.

4.3.2 Clarifying Design Standards

In a Level 2 assessment, clarity about the targeted design standard(s) for the protection against the flood hazard(s) under consideration is important because it drives both the benefits ("avoided damages") and the costs of the interventions. The choice is ultimately a policy decision on not only what is feasible within the budget and other constraints but also what is acceptable in terms of remaining risk for a specific context. Some countries have a system of established (or even legally adopted, as in the Netherlands) flood protection standards for different types of infrastructure systems. These standards are often derived from a mix of considerations including economic costs and benefits, individual and societal safety, and risk perception (see examples in Kazi et al. 2022).

Whether these standards exist and whether they should be adhered to in a Level 2 assignment should always be checked. In many other countries, however, these standards are defined on a project-by-project basis and are derived more iteratively during the programming of interventions. In that case, generic international guidelines (such as the Eurocodes)[1] can be used as a first step, but these should be tailored to the current and future local context in discussion with the stakeholders, and further iteration may be required during and after the Level 2 assignment.

BOX 4.1

Addressing the Climate Adaptation Deficit in Dhaka, Bangladesh

An important aim of a flood hazard and risk assessment is to highlight the importance of additional investments in structural and nonstructural interventions to increase the resilience against floods. Exploring a wide array of interventions and defining effective strategies with a sound rationale is essential to support the dialogue with decision-makers to address the current adaptation deficit and future climate risks. The study on urban floods in Dhaka has addressed this in a comprehensive way and has clearly highlighted the need for investments to close the adaptation deficit (Dasgupta et al. 2015).

Dhaka, the Bangladesh capital, is one of the world's rapidly growing megacities. Populated with over 20 million people, it is located in central Bangladesh's Ganges-Brahmaputra-Meghna river delta and has a tropical monsoon climate. The city suffers from chronic underinvestment in infrastructure, including the lack of a well-functioning drainage system. Urban floods and waterlogging therefore occur frequently following intense rainfall events in the monsoon season every year, bringing city activities to a standstill. During monsoon season, high river levels prevent gravity drainage through the sluice gates, and the drainage of the city primarily depends on the performance efficiency of the drainage pumps and its internal drainage system. The root causes of the drainage issues are multifaceted—with the main culprits being strong urban growth in recent decades without consideration for drainage pathways; limited funding for maintenance; clogging by solid waste, siltation, and plastics; and a fragmented governance structure.

To remedy this situation, detailed modeling of the drainage system in and around the city has been carried out for existing and future scenarios to identify the urban drainage priorities and investment needs. These results were used to assess not only the damage to the urban built environment and infrastructure but also the impacts on the health and incomes of Dhaka residents and daily migrant workers. The study explored both structural and nonstructural measures to manage the risk of flooding and tackle the root causes of the drainage challenges. Because undeveloped land is scarce in Dhaka, the conveyance-centric approach with mainly pipes, canals, and pumps has been considered appropriate for this setting. It is necessary to further enlarge this capacity by adding more pump capacity as well as more conveyance capacity in the drainage system itself. The study has also recommended a set of nonstructural interventions including improved solid waste management and general maintenance of the conveyance system. In addition, alternative and more nature-based solutions to delay, divert, and detain runoff have been proposed to create a more robust drainage system.

The study has clearly highlighted the importance of implementing additional investments to close the adaptation deficit. It also revealed that investments to address this deficit will pay off substantially by reducing future damages and losses. This study greatly benefited from the involvement and contributions of many stakeholders from Bangladesh. These stakeholders have provided valuable inputs on the existing drainage issues, the hydrological analysis, current plans, and cost estimations for adaptation.

Flooding in Dhaka, Bangladesh

Source: © S M Mehedi Hasan / World Bank.

4.4 MODELING POTENTIAL INTERVENTIONS

Once a range of potential interventions has been identified and a framework of indicators established to further select appropriate interventions, the next step is often to begin the process of defining the short list of possible interventions in more detail in terms of the likely structures, layout, dimensions, and so on, which will enable a comparison of outline costs and expected benefits. Typically, a simple single solution will not be sufficient to resolve the problem or may prove to be unsustainable, and a mix of measures may often provide the most effective and sustainable solution. These need to be identified and assessed in combination to ensure the appropriate balance.

4.4.1 Advantage of Direct, Location-Specific Modeling

In defining an optimal set of interventions, it can sometimes be helpful to start with specific packages of interventions to understand the potential and impacts of various strategies. It may also be useful to start with extreme implementations of the interventions to help clarify not only how effective they could be but also what the negative impacts might be. In an urban setting with a river flowing through the city, potential (extreme) strategies that could reduce the risk include:

- Build embankments and floodwalls to protect against flood levels
- Widen and deepen the river to lower the flood levels
- Acquire the land in the flood zone and resettle the population in this zone.

Once the advantages and disadvantages are considered in a qualitative way (that is, typically without analytical work), a more balanced mix of measures can be taken forward and evaluated in more detail using modeling tools with quantification of the appropriate set of indicators.

In the framework of urban flood risk assessments, the ***avoided damages*** and ***affected people*** are the most commonly used direct benefits used as indicators of the proposed interventions. To quantify the direct benefits of a proposed intervention for current and future scenarios, it is possible to adjust the damage frequency curve for a certain area by assuming that a certain intervention provides a certain level of protection (say, up to a 10-year or 100-year event). However, this approach has limitations, and despite its strategic usefulness, it requires the damage frequency relationship to be based solely on the exposure that will benefit from the intervention. It also fails to reflect the potential benefits from the intervention during events above the design level—for example, a flood defense embankment that will fully protect a community up to a 10-year event but will also reduce the amount of flooding that would reach the community under a 20-year flood event and beyond. There may also be benefits to wider communities that may not be directly protected by the intervention and would therefore not be included but may nonetheless receive some benefit under certain conditions. For example, an embankment designed to fully protect a community may also have partial benefits to others by reducing if not preventing the flooding to them.

It is therefore recommended that if the intervention can be reflected through direct modeling in some locally specific, realistic, and meaningful way, assessments of risk with and without the intervention are fully modeled and compared to provide a more realistic estimate of the benefits accruing. This not only enables a direct comparison of the risk with and without the intervention but also reflects the residual risk—showing the spatial distribution of the effects as well as whether, and where, any negative impacts may occur in other parts of the catchment.

4.4.2 Modeling by Type of Intervention

It is usually possible to reflect commonly adopted interventions in some way through modeling—and by introducing modifications to the setup of the hazard (Chapter 2) and risk models (Chapter 3) for the baseline situation—as follows (either individually or in combination):

Land use changes
that increase or decrease the impermeable surfaces in an area will change the amount of infiltration that will take place and can significantly alter the volume of runoff created within an urban area. Meanwhile, changes in the drainage characteristics—such as improvements to drainage systems or simply allowing rainfall landing on roofs to run off into drainage system or directly onto roads or other bare surfaces—will dramatically increase the rate of runoff.

Urban greening
such as the introduction of urban forests and changing farming practices, among others, can be represented in two ways: One is through the hydrological stage by decreasing or increasing infiltration losses and increasing baseflow. The other is by altering friction coefficients in the hydraulic model to reflect changing runoff rates.

Pumps or weirs
are often represented as a 1D element within a model and have a specific module within the modeling software to represent them in detail. Where storage and attenuation are considered outside of the direct model domain, the changes can be represented through the hydrology (that is, adjusting the inflow hydrograph shape) and applied either at a point inside the model domain or as a boundary condition at the edge of the model such as a pumped system that discharges directly into the sea.

Sustainable drainage systems
such as rainwater harvesting, soakaways, permeable paving, retention and infiltration areas, and others attempt to replicate natural processes. These can therefore be simulated in much the same way as land use change.

Improved maintenance works
such as regular dredging, cutting vegetation, and removing garbage from drainage systems can be represented by changing cross sections (for example, dredging to deepen the channel) or changing roughness coefficients to perhaps represent cutting vegetation. This approach will represent more or less flow through the modeled drainage system.

Enhanced flood forecasting and early warning
can be assessed with well-established, often empirical methods for valuing the benefit in the literature that could be employed. This provides a quantified benefit in terms of a likely value rather than an absolute value. Some caution should be taken when attributing the benefit to a single part of the forecasting, early warning, and response chain, because it is easy to double-count benefits or overestimate them.

Large-scale green, blue, and gray interventions
for increased storage, attenuation, and discharge capacity—such as restoration of wetlands; upstream reservoirs; river diversion, deepening, or widening; new or realigned embankments; and pump stations—can be represented by (1) imposing the feature or multiple features onto the DTM that underlies the two-dimensional (2D) model domain, or (2) changing cross section profiles in a one-dimensional (1D) part of the model.

Increased community resilience
through flood forecasting, early warning, and emergency response; property-based protection; and community planning and awareness, although less tangible, can be reflected through the risk modeling process by changing vulnerability curves or other aspects of the exposure data. For example, one could reduce the value of contents that would be damaged during a flood to reflect the community's response to a flood warning. Although difficult to quantify, these types of interventions can sometimes be more easily reflected on a larger scale, using broad assumptions and principles that have been demonstrated using empirical relationships.

4.4.3 Importance of Robustness Analysis

A more sophisticated analysis, to gain deeper insight into how uncertainties affect the decision-making around interventions, is a robustness analysis (for example, Hallegatte et al. 2012; Sayers, Galloway, and Hall 2012). This analysis quantifies the extent to which the performance of interventions is robust for future (deep) uncertainties. Whether or not such an analysis is useful and of added value depends on the specific case. If there are large uncertainties regarding future climate change conditions and/or socioeconomic scenarios, then incorporating a robustness analysis as part of a Level 2 assessment can be useful to quantify the extent to which the performance of the intervention(s) is robust to future (deep) uncertainties.

For this analysis, a full range of possible climate conditions and socioeconomic development must be considered. Various metrics can test the robustness of interventions (see, for example, McPhail et al. 2018). Interventions that perform well under a wide range of possible future scenarios are preferable to interventions that may generate large benefits for specific future scenarios but do not perform well for other scenarios. Climate change scenarios and socioeconomic scenarios should be based on literature—for example, existing development plans and regional climate projections. Regional climate projections should use appropriate parameters of change when applied to flood risk management.

BOX 4.2

Testing the Robustness of Different Interventions in N'Djili River, Democratic Republic of Congo

A Level 2 assessment for the N'Djili Basin in Kinshasa has been a good example of testing the robustness of different solutions in view of large future uncertainties. In this assessment, the urbanized part of the N'Djili River catchment in Kinshasa was the focal area.

The capital of Democratic Republic of Congo is poised to become the largest megacity in Africa by 2030, being the fastest growing urban system in Central Africa. The N'Djili River exposes the surrounding communities in Kinshasa to consequences of flooding and erosion of surface soil. Recent extreme events, such as the one in 2015, caused many fatalities, destroyed property (with losses in the millions of US dollars), and affected the water supply system in this catchment (World Bank 2019, 2021).

The urban part of the N'Djili watershed covers an area of around 70 square kilometers and is around 12 kilometers long, while the whole watershed covers an area of around 2,190 square kilometers. The urban watershed is characterized by high population density and growth, which is cause of increasing land use change, informal settlement, pollution, erosion, and disturbance of water runoff patterns. A detailed 1D-2D modeling exercise with detailed topography data of the entire urban area has been set up to perform flood hazard and risk mapping of the N'Djili River.

Flooding in the Urbanized Area of the N'Djili River Basin in Kinshasa

Source: City of Kinshasa.

In the modeling approach, special attention was paid to the scenarios for future risk mapping. The socioeconomic and land use development of the city in particular are uncertain in this fast-growing city. Thus, very different and contrasting land use scenarios have been generated, from planned to unplanned organic growth. To capture this uncertainty, a set of 45 scenarios was developed based on three different climate change scenarios, three socioeconomic development scenarios, and five land use options. The risk analysis for the baseline conditions showed that these 45 scenarios generated three distinct groups of risk profiles. Out of these groups, three representative scenarios were selected for further analysis of the interventions.

Next, a long list of interventions was created based on the insights from the flood hazard and risk mapping. These interventions were tested individually but also in combination. They included an upstream storage basin, downstream levees, resizing various bridge crossings and floodplain sections, and resettlement options. A set of 25 alternatives were evaluated against the three representative future scenarios. Economic, social, and environmental benefits were evaluated with various indicators (such as the plan with lowest regret, the highest maximum performance, and the highest average performance) providing useful insight in promising solutions for more in-depth feasibility studies.

The assessment for the N'Djili River is part of a wider support to the Democratic Republic of Congo and has been informing the ongoing dialogue to increase urban resilience in Kinshasa.

4.5 COSTS AND BENEFITS OF INTERVENTIONS

4.5.1 Costs

Defining the costs of interventions is often an important part of a Level 2 assessment and should be carried out as accurately as the data allow. Since the detailed design of the interventions will not be known at this stage, the estimation of costs will still be quite uncertain. It is important to recognize these uncertainties when the costs are used for any planning purposes or used in any form of cost-benefit analysis.

Costs for structural interventions must include both initial capital costs and ongoing, long-term maintenance costs. Capital costs are spent to build the intervention, and these could be not only construction costs but also land acquisition costs. After completion of the intervention, operation and maintenance (O&M) costs will recur every year. These costs can involve regular maintenance works like grass cutting, painting or small repairs, and operating costs (for example, manpower for operating a structure, fuel, power, and so on). They may also include more significant maintenance costs that occur less frequently but can still be annualized for the purpose of the analysis.

4.5.1.1 Capital Costs

The capital costs of interventions can be quantified in different ways. Depending on the level of detail in a Level 2 assessment, two ways are often possible:

Using other project costs and scaling these appropriately—
for example, by volume (cubic meters) for reservoirs, by area (hectares) for mangroves, by length (meters) for embankments, or by volumetric rate (cubic meters per second) for pump stations

Using unit costs for different materials—
for example, by volume (cubic meters) for excavation, fill, or concrete; by area (hectares) for mangroves; or by area (square meters) for land acquisition. Other costs of design and supervision can be added based on information about these costs from similar assignments.

For certain interventions, there are some country-specific unit cost estimates, such as for embankments (Hillen et al. 2010) and for a wide range of flood adaptation measures, including floodproofing of buildings, flood protection, beach nourishment and dunes, NbS for coastal ecosystems, channel management and NbS for riverine systems, and urban drainage (Aerts 2018; World Bank 2021). However, it will always be required to check any existing unit cost estimate against local market conditions.

Depending on the situation, other direct costs could surface, which can be significant in the total costs of the interventions. Land acquisition or resettlement costs can be a substantial part of the costs, especially if the interventions need significant space in a densely built city environment. These costs are often location-specific and can only be defined based on local information.

4.5.1.2 O&M Costs

The inclusion of O&M costs is essential in the total cost estimates of interventions because these can be significant if the lifetime of the construction is accounted for. In a Level 2 assessment, these annual costs are often expressed as a percentage of the capital expenditures based on reference projects or expert judgment. The percentage depends on many factors, including the type of structure, its method of construction, and the environment in which these structures are present.

Aerts (2018) provides a comprehensive overview of different intervention types for flood management with indicative values of maintenance costs based on an extensive review. Coastal and riverine flood control structures with high O&M costs include pump stations, storm surge barriers, or sea dikes with revetments (for which, for example, annual O&M costs 1-5 percent of capital investment), whereas grass-covered embankments in a relatively calm environment need much less maintenance (0.01-1 percent). The maintenance costs of urban drainage range from 0.5 percent to 10 percent of investment based on this review.

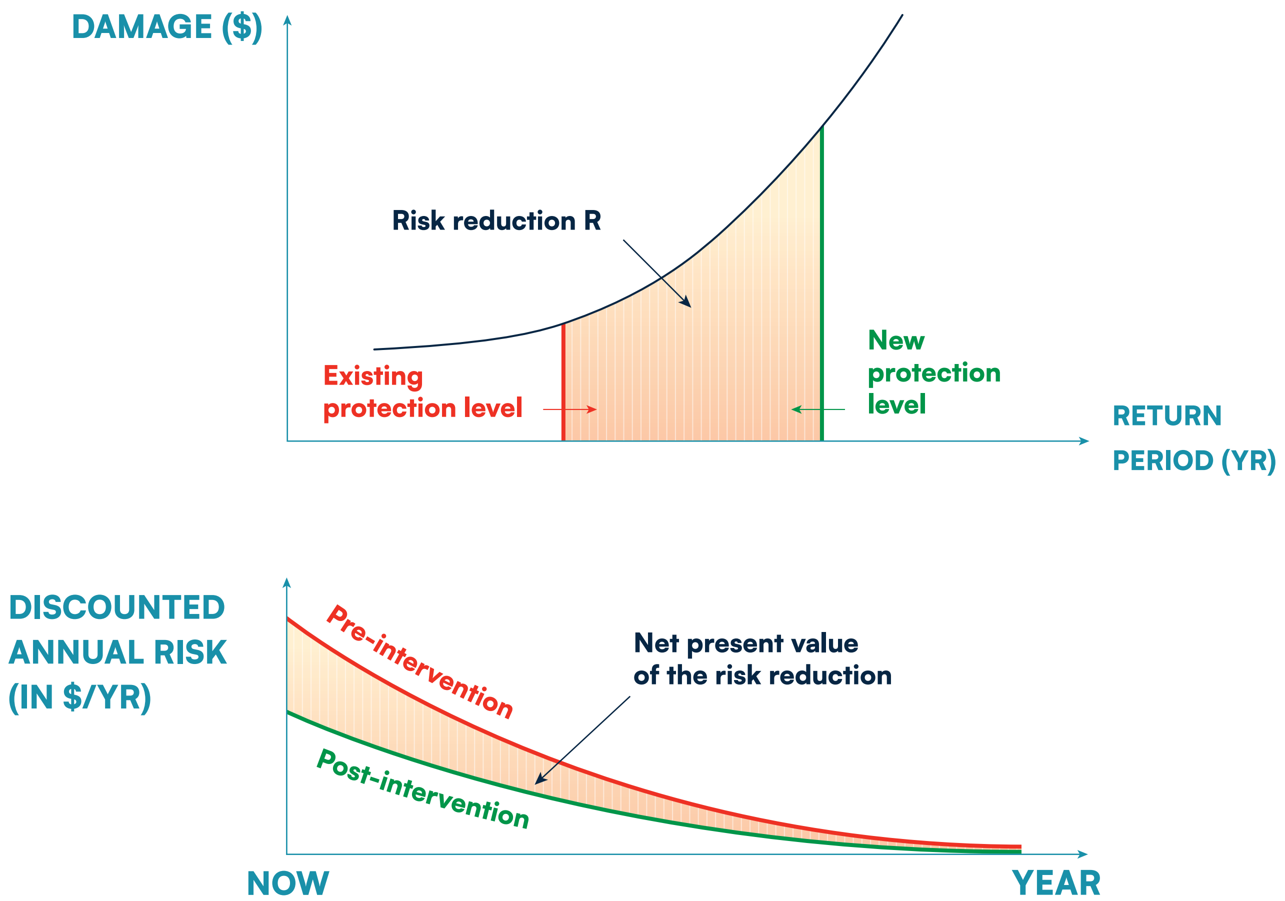
4.5.2 Benefits

A Level 2 analysis can use various quantitative risk metrics to estimate the benefits of the interventions. Commonly applied risk metrics are the reduction in economic risk and reduction in affected people. The economic benefits (that is, risk reduction) of interventions are a yearly recurring effect (figure 4.4), and the net present value (NPV) of this benefit can be determined using an appropriate discount rate.

The costs and benefits can be used in a cost-benefit analysis to derive relevant economic metrics such as the internal rate of return or the NPV, with metrics being influenced by the discount rate chosen. Because the various inputs of such an analysis are inevitably uncertain, it is not only important to have carried out sensitivity testing throughout all the various stages in the analytical process (to understand the likely range of possible results as well as the scale of the uncertainty in these inputs), but it is also often advisable to investigate uncertainty in the parameter choices for estimating benefits and costs. For example, this could include reduction in damage, discount rate, capital and O&M costs, as well as potentially different future socioeconomic or climate scenarios.

For traditional cost-benefits analysis, risk is valued in expected annual damage (EAD) or average annual losses (AAL), and the risk reduction benefits are valued as the reduction of EAD or AAL. This approach does not consider the risk aversion of individuals who may place a higher value on risk reduction (especially relevant for individuals who are highly vulnerable to floods). Not factoring in individuals with higher risk aversion may lead to the recommendation of measures that favor those who are already better off. Therefore, it is recommended that the benefit-cost ratios and other relevant economic metrics of interventions based on such assessment be expressed as a range, which is always preferred above a single number.
This promotes understanding of what the variation in benefit-cost ratio could be, depending on certain assumptions and how likely it is that the intervention will be economically justified under a range of scenarios.

Figure 4.4 Schematic Representation of Risk Reduction from a Structural Flood Risk Intervention



Note: In this figure, risk reduction equates to the economic benefits, on a yearly recurring basis, of structural flood-risk interventions such as improving a drainage system or raising an embankment.

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In addition, focusing only on a reduction in damages will not provide a full picture of costs and benefits. For example, richer areas may be favored for protection since they have a higher amount of hard assets at risk. Therefore, the breadth of the benefit analysis should go beyond traditional cost-benefit analysis as outlined above and also assess, where practical, additional co-benefits. To the extent possible, additional environmental and socioeconomic benefits (co-benefits) derived from the solutions, such as livelihoods or jobs generated, poverty reduction, improvement in urban air quality, less cooling usage, carbon sequestration, and increase in livability (such as access to public spaces, leisure, and the like) should be included meaningfully within the prioritization process. The impact of any intervention on economic and urban growth should also be assessed and careful consideration given to the discount rate employed.

The aim of a Level 2 assessment is not to develop a detailed cost-benefit analysis but rather to provide policy makers with enough information for an initial comparison of potential investment scenarios and at least provide a ranking of measures that includes their prefeasibility effectiveness and costs under a wide range of potential future scenarios.

4.6 ENVIRONMENTAL AND SOCIAL IMPACTS

Structural and nonstructural interventions may generate environmental and social impacts, which can be very important for the overall feasibility of the solutions. During a Level 2 assessment, it is therefore fundamental to understand the main environmental and social implications of potential interventions and which options exist to reduce the unwanted impacts as much as reasonably possible through the design of the interventions, but also to maximize the creation of additional environmental and social benefits.

4.6.1 Resettlement and Land Acquisition

Two of the major impacts of structural interventions in any urban environment are resettlement and land acquisition.

Resettlement. Urban environments are generally densely urbanized without much space available for often-large green or gray infrastructure like retention basins, swales, new drainage canals, or outlet structures. People may live near existing drainage systems or embankments where simply widening or enlarging these structures may cause direct impacts such as loss of land and need for resettlement. In addition, a substantial percentage of the urban population in many cities may live in informal settlements, which also tend to be relatively flood-prone areas where interventions are likely to be required.

Resettlement of the population is a complex and sensitive issue and is therefore generally avoided. If it is unavoidable, it is critical, at an early stage, to generate a clear and detailed picture of the scope for resettlement for a specific solution with detailed mapping of the population characteristics and their status. Also, a layout of the required steps and time necessary to complete this entire government process—as well as an understanding of its risks—is essential for the overall feasibility assessment of options requiring resettlement (Correa, Ramírez, and Sanahuja 2011).

Land acquisition. Similarly, structural interventions may require land for construction of new infrastructure or a sediment disposal site for polluted dredged sediments from the drainage system. New drainage channels or widening existing ones require strips of land to be acquired throughout a dense urban fabric. Also, green infrastructure solutions such as retention areas often need large surface areas to be effective. Acquiring the land for these interventions can be time-consuming owing to the absence of detailed and up-to-date land ownership registers, a complex government process of payments through various layers of government, and the costs of acquiring land can be high.

The discussion above highlights that minimizing the scope for resettlement and/or land acquisition is generally favored during the search for feasible options. Some practical examples of ways to do this at different spatial scales are to enlarge drainage channels by replacing slopes with vertical walls or to reduce inflow by taking measures upstream of the city (forestation, upstream retention, and so on) and redirecting flows to other less urbanized areas or creating bypass systems.

That being said, unavoidable resettlement and land acquisition can also be converted into a development opportunity for the communities at risk to improve their livelihoods. Roquet et al. (2017) provide examples of successful practices in urban resettlement and land acquisition for urban development projects.

4.6.2 Other Environmental and Development Impacts

Other types of impacts may be encountered during a Level 2 assignment.

Water availability

Structural solutions for reducing flood risk may affect other water-related aspects of the system. For instance, dredging may increase the river's flow capacity during floods and thus be positive from a flood risk perspective but also lower its water levels during the dry season. Poorly considered dredging can therefore have a detrimental effect on water resource availability and agricultural activities given a lower groundwater table in areas surrounding the river.

Sediment and debris pollution

Dredging is a commonly used response to flooding from rivers and watercourses, particularly where the channel is seen to be filling up with sediment. This approach should always be carried out with caution because it can often result in unexpected or even negative consequences. For example, by simply dredging a section of river that is thought to be causing flooding, the result is a deeper but usually slower-moving stretch of river flow. As a result, the next time it floods, this section acts like a sediment trap because it has slowed down the flow rates, encouraging sedimentation.

Furthermore, dredging a section of river inevitably creates a steeper bed slope at the upstream end of the dredged section and locally increases velocity there, which often results in increased erosion at that point, in turn deepening the channel further and moving the deepened channel upstream along with the localized high-velocity section. If this continues to travel upstream, it can have serious consequences on any upstream structures (bridges or embankments).

The downstream end of the dredging must also be carefully considered because the water level along a stretch of river is most often controlled by a downstream feature, which may not be evident during normal flows, but during a flood, the upstream water levels are likely to be controlled by a bridge or some other solid feature. No amount of dredging will increase the flood flows that the downstream feature will allow to pass, and so the flood levels in the area will remain the same as before dredging.

Vegetation removal and dredging of drainage canals can also produce large amounts of sediments, debris, and other materials. These sediments may well be polluted in an urban environment and thus must be treated with care to avoid negative impacts on population health and the surrounding environment. If the sediments are not polluted, then direct distribution of sediments in rivers or at sea or reuse (for example, for construction purposes) may be an option, but the impacts of these activities must be carefully assessed and minimized.

However, it is bad practice to leave the sediment permanently along the riverbank. This can form semipermanent embankments that may alter the flow dynamics both upstream and downstream and potentially make flooding worse elsewhere. It can also create the false impression that the areas behind the sediment banks are now protected and are safe to live in. This can be a grave mistake because the unconsolidated sediment—likely consisting of fine, highly erodible particles—may appear solid and stable but may be highly susceptible to sudden failure and potentially rapid inundation of the floodplain that was formerly open but now heavily developed.

Urban development challenges

Flood risk management may also affect urban development. If areas become better protected against flood risk because of structural interventions, these areas are likely to become more attractive for further urbanization and economic activities. The same holds for NbS in flood risk management (such as urban parks or restoration of natural drains in urban environments), which may generate positive environmental and societal impacts. It will therefore be important to make a good fit between the proposed solutions and a broader strategy of sustainable urban development.

4.6.3 Applicability in a Level 2 Assessment

Although a Level 2 assessment does not aim to do a full environmental and social impact assessment, it should provide some baseline information on the likely positive and adverse effects of proposed solutions. It should also look at the governing frameworks for these assessments and align the analysis with these frameworks for further analysis. With the potential solutions in mind, an initial scan may be adopted to generate a list of critical environmental and social aspects. These aspects can then be further described for each solution under consideration.

The flood risk assessment outputs may help quantify some of these impacts. For example, the hydrological or hydraulic models applied in the risk assessment can provide insight into the changes in flows and water quantities (due to reservoirs or storage upstream, for example) or the land required for expansion of urban drainage system. In other cases, a more qualitative assessment may be needed to assess the potential impact.

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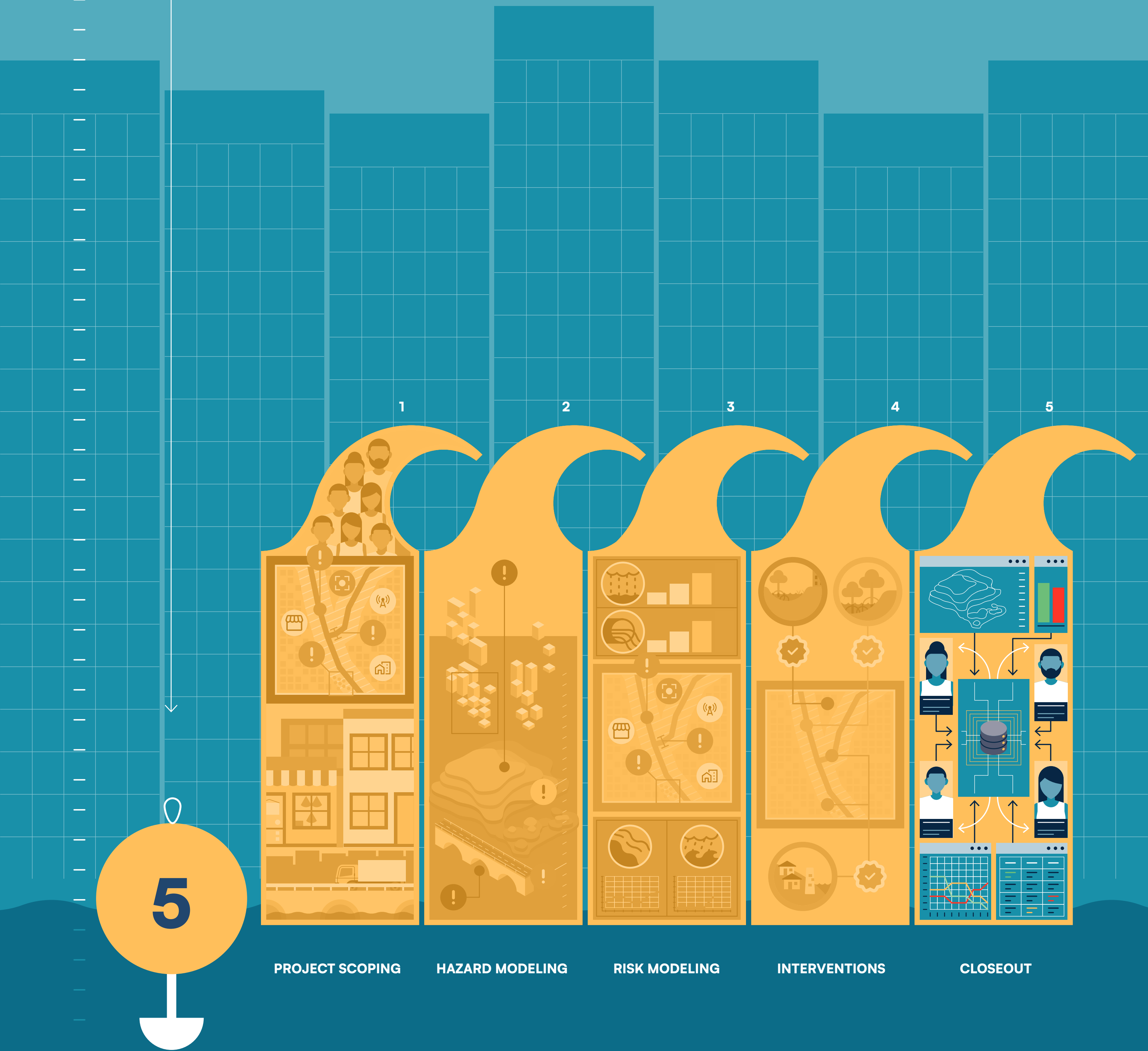
ENDNOTES

1 The Eurocodes are the 10 European standards specifying how structural design should be conducted within the European Union. See https://www.en-standard.eu/eurocodes/.

CHAPTER

PROJECT MANAGEMENT ISSUES AND CLOSEOUT



5.1 BID PREPARATION AND SELECTION

It may be possible (or preferable) to carry out simple Level 2 hazard and risk assessments in-house within the organization, but more usually, a consultancy firm (or occasionally a consortium providing specialist skills or resources) will be required to carry out the work. Regardless of the approach, it is necessary to develop a terms of reference (ToR) for the assignment to ensure all parties are clear on the objectives, scope, and expected outcomes. The ToR need not be a detailed document for an in-house assignment. However, when commissioning a firm to carry out the work, the ToR will form a legal part of the contract and must be clear, specific, and accurate.

The ToR should provide sufficient information and detail for tendering firms to understand the background and context of the assignment and the likely scope of work involved. It must include a clear statement of the objectives and intended use of the study results. This is an important part of the ToR; tendering firms will use it not only to help understand the overall expectations of the assignment but also to define what a successful outcome needs to look like.

The ToR should set out the various stages or phases of the project and outline the main expected activities. However, it should avoid going into too much detail about how the assignment should be carried out. It should instead provide detailed definitions of the intended analytical or reporting outputs, including the level of accuracy, detail, and resolution that will be required.

5.1.1 Selecting Consultants, Gathering Local Knowledge

A Level 2 urban flood risk assignment requires a balanced team of consultants with a range of skills and competencies. Core skills are flood (hydrological and hydraulic) and risk modeling; prefeasibility design of green, blue, and gray flood control or drainage infrastructure interventions; environmental and social expertise; and urban planning. But urban flood risk interventions often also provide an opportunity to add value to urban living conditions. For example, stakeholders may have ambitions for particular areas in the urban environment such as more recreational space, improved water supply, and so forth. These ambitions should be acknowledged at an early stage and may require that different specialists (for example, drinking water or sanitation specialists, urban landscape architects, and others) be added to the consultant's team requirements to integrate these knowledge fields into a comprehensive plan for urban flood risk management.

During preparation of the ToR, all efforts should be made to collect or be aware of as much relevant information and data as reasonably possible. In many countries, it is challenging and time-consuming to acquire data from governments or other sources. Early identification of and access to relevant data from local stakeholders should therefore have high priority during tender preparation. To those ends, site visits and intensive discussions with the stakeholders are strongly recommended regarding the functioning of the existing river or coastal flood protection infrastructure and urban drainage systems as well as any associated challenges (or flood risk management issues). These discussions should explore data availability for these systems, the urban environment at risk, and timelines for access—resulting in a clear understanding of the overall context for the assignment and its outcomes.

In addition, a review of earlier assessments and interventions should be carried out to provide up-to-date insights into what has been done to date and prevent duplication of work. A review of existing data sources (including any existing numerical models of the area of interest) shall also be carried out to identify what additional data collection must be included in the scope of work and how the project can build on previous assignments. Based on this information, a ToR must be drafted and discussed with the stakeholders to get their input and feedback.

Finally, the safety and security situation in the specific urban and country context is important because a Level 2 flood hazard and risk assessment requires local knowledge and should include field visits by senior technical staff as well as firsthand discussions with local knowledge holders. International consultants may often associate with local consultants to carry out or facilitate these tasks. Official travel advice and regulations provided by national governments dictate the possibilities and limitations of international consultants carrying out work or directing and supervising others to work in countries abroad. Generally, the international consultants must provide duty of care to their local subcontractors, but the required level may differ depending on individual country regulations. Travel or restrictions on hiring local contractors may impose specific limitations on the envisioned activities and may require tailoring the ToR accordingly.

5.1.2 Key ToR Features and Lessons Learned

A ToR includes several key features:

CONTEXT:

- What is the country context, what are the existing and potential future challenges of urban flood risk, and who are the main stakeholders?

PURPOSE:

- What is the objective of the assessment, and who will use the output?

SCOPE:

- What is the geographical (scale) and temporal (existing, future) scope?
- What flood hazards (pluvial, coastal, fluvial) and risks (affected population, casualities, direct or indirect damages, and critical infrastructure) are included?
- Who are the stakeholders, and when and how should they be engaged in the assignment?
- What outputs, such as flood hazard maps and risk metrics, are expected?
- What types of interventions (gray-green-blue infrastructure solutions, nonstructural solutions) shall be considered?
- What level of detail is required for the hazard and risk assessment—horizontal resolution, type of modeling to use, quality of the digital terrain model to use, number of small-scale features included in models, and number of events, among others?
- What level of detail is required regarding the design, costing, and assessment of potential impacts of structural interventions?
- What are the needs for capacity building within the agencies or among other stakeholders?
- What is the level of engagement and interaction with government counterparts and other relevant stakeholders in the country?

DELIVERABLES:

- Which reports, datasets, prefeasibility drawings, visualizations, and the like should be developed, and what do the acceptance processes (reviews) of these products look like?

TIMELINE:

- What are the deadlines for reporting, feedback, and meetings with stakeholders?

CONSULTANT'S TEAM REQUIREMENTS:

- Which staff competencies and skills are required to cover relevant disciplines as well as local or global experience requirements?

IMPLEMENTATION ARRANGEMENTS:

- What is the contracting agency, what is the role and organization of stakeholders, and what is the country's safety and security situation?

A review of past natural risk assessment projects has revealed several lessons learned from earlier assignments for preparing a good ToR:

Be specific
about the purpose, expected analysis, level of detail, outputs, and so on of the hazard and risk assessment—to be further detailed and confirmed during the inception stage and clearly documented within the inception report. The importance of the inception stage of the assignment should not be underestimated. This preliminary stage allows the consultants who will carry out the work an opportunity to develop a fuller understanding of all aspects of the assessment and to confirm or adjust the detail of their methodology as necessary. The overall scope will not change as a result; however, there may need to be clarifications or final agreements regarding some technical or project management details.

Emphasize the need for hazard and risk model validation
to obtain realistic results despite difficulties due to lack of data.

Clearly state the expectations for interventions—
whether structural (gray and nature-based) or nonstructural—and the level of detail required in the functional and technical description, dimensions and layouts, and drawings or visualizations.

Request a project-specific quality assurance and quality control
section within the team's proposals that defines the approach to reducing the risk of errors in data processing and to obtaining good-quality documentation.

Request clear explanation
of how uncertainties will be dealt with throughout the entire chain of hazard and risk modeling (for example, modeling uncertainties and future climate and socioeconomic scenarios).

Request a diverse team of specialists
that is not only tailored to the specific urban flood issues but also able to address the stakeholders' other context-specific ambitions or needs, which may be combined with flood management interventions.

Be clear about requirements for and delivery of data and models
(such as regarding formats and software). Stipulate the use of open data and software as much as possible.

Be specific in selection criteria
to ensure that the quality of the bidders' proposals can be distinguished (for example, in terms of staff competencies, experience with similar projects, and key aspects of the technical proposal).

Prepare a preliminary time and cost estimate
for the various tasks of the assignment to help align the overall budget with the requested details in the various activities.

Prepare all existing data or models
from the various project partners—often a time-consuming task—to hand over during initial stages of the project.

Remember, the purpose of the ToR is to state all requirements in a way that allows the firm to cost the work. The more clearly they are defined, the more accurately the firms will be able to price the work, and the less they will need to load the cost to cover their risks through misunderstanding.

Once proposals from various bidders are received, the selection of a firm can be initiated. A good mix of technical and nontechnical people for the evaluation of an urban flood risk proposal is essential. A Level 2 assessment covers a wide range of technical and nontechnical disciplines such as hydrology, hydraulics, risk assessment, environmental and social impacts, costing of interventions, and institutional aspects. Therefore, a varied team for evaluation of the bids is required to make a good selection.

5.2 PROJECT EXECUTION PHASE

5.2.1 Consultant Oversight

Once a team of consultants is on board, managing an urban flood risk assessment requires various skills in the client-side team that oversees the consultant's activities.

These skills depend on the specifics of the assignment, but generally speaking, the following skills are always required in guiding this assignment:

- Ability to engage with local stakeholders and to gather context-specific knowledge
- Experience in flood hazard and risk modeling and design of interventions
- Managerial skills to keep track of planning, budget, and so on.

It is important to recognize that conducting an urban flood risk assessment is not an exact science or a standardized product. Also, urban flood risk assessments are often applied in data-poor environments, which requires the ability to interpret modeling results and use expert judgment to deliver credible results. From an oversight perspective, it is therefore paramount to guide the consultant by providing experienced resources to ensure high-quality products and alignment of the process with the envisioned time and budget available.

5.2.2 Stakeholder Management

The characteristics of a flood risk assignment require a thorough and frequent interaction between the consultant and stakeholders to discuss the best methodological approach for the specific situation. Regular meetings are also essential to guide the process of such an assignment.

The involvement of stakeholders throughout the process helps in three fundamental respects:

To acquaint stakeholders with the approach and the results of the risk analysis.
Stakeholders should be able to provide feedback as to whether the results of the risk analysis are realistic and recognizable—aligned with their own understanding of local risks—which is pivotal for creating a joint factual basis regarding the existing and future risks in a city environment. Such a basis is essential to move toward interventions supported by the stakeholders.

To get input and feedback from the stakeholders on the feasibility of proposed solutions.
Stakeholders often know very well the existing structural and nonstructural systems to prevent the impacts of floods, and they can provide valuable feedback on what may work and may not work to increase urban flood resilience.

To discuss other ambitions of stakeholders in the urban environments at risk. Through discussions, integrated visions and prefeasibility designs can be created by linking investments in flood risk mitigation to other urban needs, developing a combined investment approach, and thereby further enhancing the support for these interventions.

During inception of the project, it is strongly recommended to develop a clear stakeholder management plan, including the roles and responsibilities of all parties involved (stakeholders, direct beneficiaries, consultant, and client), milestones for discussion, and agreement on next steps. With that being said, it is recommended to check the willingness of different organizations to provide support and information before the study begins, because experience shows that lack of support and information is often a bottleneck for consultants.

5.2.3 Quality Assessment and Control

During the project execution, a robust review process for deliverables is critical for high-quality outputs. Typically, an urban flood risk assessment produces three different types of deliverables: (1) reports (inception report, modeling report, and the like); (2) models and analytical work (hydrological or hydraulic models and risk models); and (3) output datasets (derived hydrological data, flood hazard or risk maps, and risk metrics).

The first step in the review process lies with the consultant, through its own quality assurance and quality control process. It is important to ensure that the consultant adheres to its own internal quality procedures and makes explicit how this process has been carried out, not only for reports but also for modeling schematizations and modeling results. The consultant should also comply with industry good practice, follow normal expected standards and procedures, and be able to demonstrate these practices at any stage during and for a reasonable period after the completion of the assignment. This demonstration would include keeping understandable and logical modeling logs, ensuring logical and sensible directory and file naming conventions and formats, and implementing standard graphic information system (GIS) protocol for all geospatial datasets.

The next step is the review process by the client or beneficiaries. Providing sufficient time for review and a logical structure for organizing the comments and suggestions for improvement (for example, using standardized comment sheets) are important to add value to the deliverables' overall quality and to ensure a smooth process with the consultant.

5.2.4 Lessons Learned

Review and discussions of past urban flood risk assessments have revealed the following nonexhaustive list of specific lessons learned for the execution phase:

- Ensure that the importance of the project scoping and inception stages of an assignment are acknowledged and that these stages are well documented. This is an opportunity to refine, agree upon, and finalize the methods, available data, timeline, any project risks or constraints and so on, as well as to be clear on both sides exactly how the assignment will progress and what the expectations are. This is only achievable if sufficient time is assigned for this activity and should include formal approval and sign-off to ensure the outcomes are recognized and successfully implemented.

- Allocate enough time to assess the hazard and risk results once available and, if necessary, fine-tune these to arrive at credible results. The interpretation or explanation and the sensibility checks of hazard and risk modeling results (both consultant and client) are important. It is easy to take the results at face value without giving them sufficiently rigorous critical examination, which can lead to less-robust outcomes.

- Check that the consultant follows their own quality assurance and quality control procedures before releasing deliverables for client review. This should be properly evidenced as part of the reporting process. Efficiency can be improved by using standardized comment sheets for reviews of deliverables to organize and synchronize comments, suggestions for improvements, and responses to comments. Also, ensure that the various reviewers' and stakeholders' comments to the consultant are consistent and not contradictory.

- Allocate sufficient resources or time from the client's perspective to work with the consultant (meetings, reviews, and so on) and to meet deadlines for reviews (by the client and stakeholders) to allow the consultants time to meet their deadlines. In the same way, it is essential that stakeholders make commitments of time to support data collection, to engage in field visits, and to discuss the results and provide feedback is essential.

- Be aware of and avoid ***scope creep*** during the project (client to consultant), and only allow project change through a formal process of documentation, agreement, and approval to avoid later disagreements regarding budget, time, and deliverables (or quality).

- Organize regular meetings with the consultant to discuss interim results, with presentations (by the client and consultant) to discuss key assumptions and decisions regarding the methodology of modeling and design of interventions.

- Match the project's scope with its duration. The assignment's expected duration is often dictated by the program considerations, but its scope must be designed to realistically align with the time available.

- Be aware of and closely monitor the safety and security situation in a country (client and consultant). During project implementation, it shall always be part of the consultant's risk register, in which mitigation measures are also identified and executed.

Each urban flood risk assignment will have its own specific characteristics, but a continuous dialogue between consultant and client about project expectations and objectives—and a good focus on the interim and final project deliverables and the quality thereof during the project execution—will maximize the chances of an assignment with high-quality output and a smooth process.

5.3 PROJECT CLOSURE PHASE

The purpose of the project closure phase is to ensure that the results and findings are delivered in such a way that promotes ownership with key stakeholders and to lay the foundation for follow-up discussions and investments. It is also important to help ensure that the effort and investment in data collection and preparation, modeling, analytical work, and intellectual endeavor is not lost or wasted. The project handover phase is often a good opportunity for capacity building among stakeholders through tailored training on both the deliverables and the means of preparing them (for example, hydrology, hydraulic modeling, geographic information system, and risk-aware land use planning).

A well-structured and logical data archive of the project is therefore important to enable efficient use of this information for other purposes. The original ToR's careful description of model and data delivery and handover will be an important part of a smooth project closure. But the execution of a good data archive and handover could sometimes come under pressure owing to time and budget issues at the end of the project. It is important to realize that much of the work's value is lost if this archiving and handover are not done. A report by itself is not of much use at a later stage, especially if the model or data collected can be reused for a next phase (for example, detailing the interventions).

Lessons learned from earlier assignments for the project closure phase include the following:

- Ensure that the consultant delivers the data (for example, model schematizations and hazard, exposure, and risk datasets) with all associated metadata in a structured and logical way with clear documentation at the end of the project.
- Ensure that the data and models are delivered in a way that will allow easy retrieval for any future phases of the project (such as during project preparation and implementation) or for further use or developments by the client or the client's officially appointed consultants.
- Carry out an evaluation of the project performance and outcomes together with the consultant to identify any lessons to be learned (process and contents), and ensure that these are shared internally to improve future assignments.

It is important to realize that a project may be closed, but the project deliverables are often fed into the next steps, such as detailed feasibility and design studies and implementation of interventions. The produced data, models, and reports can be of valuable use in these steps toward a more flood-resilient urban environment.

Glossary

#

0D/1D/2D/3D: Flood modeling approaches, varying from simple zero-dimensional (0D) point or box models based on a volume balance to complex 3D models that calculate water movement in three dimensions. Hybrid approaches (usually 1D-2D) also exist that combine different model approaches.

A

ANNUAL EXPECTED DAMAGE (AED): Often referred to as the annual average damage (AAD), AED is the annualized average of all flood damages that could occur over many years. It is not a figure expected in any particular year, but it provides an indication of what flooding in an area will cost over time. It is calculated by estimating the total damages for each event, multiplied by the event probability to provide the annual damage.

B

BLUE INFRASTRUCTURE: A type of nature-based solution (NbS) that utilizes water retention to manage flood risk, such as a retention pond or attenuation feature.

C

CALIBRATION: Tuning the model parameters with realistic boundaries such that the results fit observed characteristics.

C

CONSEQUENCES: Damage to assets such as buildings, infrastructure; victims or displaced people; economic and welfare losses; and environmental damage.

D

DESIGN STORM: A “hypothetical discrete rainstorm characterized by a specific duration, temporal distribution, rainfall intensity, return frequency, and total depth of rainfall” (Law Insider dictionary, s.v. “design storm,” accessed February 11, 2023, https://www.lawinsider.com/dictionary/design-storm)

D

DETERMINISTIC: This modeling approach simulates either a single storm or a small number of statistically derived design events (such as 10-year, 50-year, 100-year, and so on). In this approach, each return period is represented by a single outcome which can then be integrated to provide risk matrices that take frequency into account. This approach is easier to conceptualize than a full probabilistic assessment and is widely used.

D

DIGITAL TERRAIN MODEL (DTM): Sometimes also known as digital elevation model (DEM), the DTM shows the bare earth elevation (after removal of objects such as trees and buildings, among others).

E

EXPOSURE: The assets, features, or facets of a community that are affected by flooding—including people, property, buildings, transportation, or any aspect that can be considered vulnerable to flooding.

G

GRAY INFRASTRUCTURE: Built structures and mechanical equipment, such as reservoirs, embankments, pipes, culverts, pumps, and canals. These engineered solutions are embedded within watersheds or coastal ecosystems whose hydrological and environmental attributes profoundly affect the performance of the gray infrastructure.

G

GREEN INFRASTRUCTURE: A type of nature-based solution (NbS) that utilizes the ability of vegetation to retain or at least slow down the movement of water to help manage flood risk, such as a mangroves, forests, or dense undergrowth, or even as simple as green roofs.

G

GREEN-BLUE INFRASTRUCTURE: A combination of green (i.e., use of vegetation) and blue (i.e., use of water retention structures) interventions that use the best of both types of flood reduction capacity to maximize the flood risk management benefits. An example of this type of feature is a wetland.

H

HYDRAULICS: The study of the movement of surface and subsurface flows in physical systems such as at coasts, in rivers, streams, storm drain networks, etc.

H

HYDROLOGY: The study of the circulation of water throughout the hydrological cycle, including processes such as precipitation, evaporation, infiltration, groundwater flow, surface runoff, and streamflow.

I

IMPACTS: Consequences of a flood hazard event or interventions, including environmental (for example, removal of polluted sediments) and social effects (for example, land acquisition or resettlement).

I

INTERVENTIONS: Actions that reduce risk either by lowering the probability of flooding, the consequences of flooding, or both. Examples in an urban context are drainage works, dredging, waste collection, and others. The scale of interventions covers catchment, urban, neighborhood, and building, and the type of intervention can be either structural or nonstructural.

L

LiDAR: Laser imaging, detection, and ranging, which is an airborne technique to measure the earth's elevation with high precision using laser pulses.

M

MAXIMUM DAMAGE VALUES: Monetary values of maximum direct damage to an asset (such as housing or infrastructure) during a flood, expressed in US dollars per square meter (US$/m^2). These values are generally based on replacement costs but factor in other variables (for example, depreciation, contents of buildings, etc.).

M

MERIT: Multi-Error-Removed Improved-Terrain, a global topography dataset based on NASA's original Shuttle Radar Topography Mission (SRTM) (horizontal resolution approximately 90 meters) in which errors of the original SRTM dataset have been reduced and accuracy improved.

N

NATURE-BASED SOLUTIONS (NBS): An umbrella term referring to features, structures, or actions that protect, sustainably manage, and restore natural or modified ecosystems, to reduce flood risk. Typical subcategories of these types of flood risk-reducing interventions are green, blue, and green-blue infrastructure. See the recent "Catalogue of Nature-Based Solutions for Urban Resilience" (World Bank 2021).

N

NONSTRUCTURAL INTERVENTIONS: Measures not involving physical construction that "use knowledge, practice, or agreement to reduce disaster risks and impacts, in particular through policies and laws, public awareness raising, and training and education." Examples are early warning systems, contingency plans, evacuation plans, zoning, insurance, and risk awareness, among others ("Structural and Non-Structural Measures," PreventionWeb, United Nations Office for Disaster Risk Reduction, https://www.preventionweb.net/terminology/structural-and-non-structural-measures

P

PROBABILITY: Chance of occurrence of flood events, often expressed as a percentage likelihood per year or return periods.

P

PROBABILISTIC APPROACH: This modeling approach typically differs from a deterministic assessment in that it considers all possible events that could cause flooding. A common approach is to create a 10,000-year time series of rainfall, river discharge, tides, and the like, using stochastic methods that capture the local variability of the relevant parameters. A key feature is the range of different conditions that can represent a specific frequency event (return period) and the spatial variation of the severity of these events. This approach provides a far better reflection of natural or seminatural processes (such as flooding).

R

REPLACEMENT (OR RECONSTRUCTION) COSTS: Monetary value to replace an asset, generally expressed in US$/m^2.

R

RETURN PERIODS: The inverse of the average frequency of occurrence; for example, the frequency of a "10-year flood" has a 10 percent chance of being exceeded every year. These days, many institutes favor the use of a percentage likelihood per year because the "return period" can be misleading.

R

RISK: The combination of hazard, its probability, and its consequences.

S

SCENARIOS: Current and possible future conditions that represent expected drivers of change, such as socioeconomic development (for example, population growth or economic development) and climate change (for example, sea level rise or intensification of rainfall). Because there is so much uncertainty relating to the estimates of future conditions, it is common to investigate a range of possible conditions under different strengths or types of drivers, either singularly or in combination.

S

SRTM: NASA's Shuttle Radar Topography Mission (SRTM) is a global gridded topography dataset (30 meters and 90 meters resolution) with low accuracy.

S

STRUCTURAL INTERVENTIONS: "Any physical construction to reduce or avoid possible impacts of hazards or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems." Examples are embankments (levees or dikes), pump stations, reservoirs, canals, drainage tunnels, and waterproofing of buildings, among others ("Structural and Non-Structural Measures," PreventionWeb, United Nations Office for Disaster Risk Reduction, https://www.preventionweb.net/terminology/structural-and-non-structural-measures.

U

URBAN FLOOD RISK: This concept encapsulates the scale and likelihood of an adverse impact associated with flooding within an urban environment, characterized by a combination of the diverse nature and complex sources and causes of flood hazard; the wide range of exposed assets, communities, and infrastructure; and the associated complexity and variation in vulnerability of these exposed elements that depends not only on their construction and materials but also their ability to cope or recover from flooding events.

V

VALIDATION: The process of checking the model results against (independent) flood data.

V

VULNERABILITY FUNCTIONS FOR ASSETS: The vulnerability function for assets is often a value between 0 and 1 as a function of one (or more) flood hazard characteristic(s), expressing the percentage of the (total) replacement costs.

REFERENCES

World Bank. 2021. “A Catalogue of Nature-Based Solutions for Urban Resilience.” Report, World Bank, Washington, DC.

URBAN FLOOD RISK HANDBOOK

ASSESSING RISK AND IDENTIFYING INTERVENTIONS