Disaster and Climate Change Risk Assessment Methodology for IDB Projects

A Technical Reference Document for IDB Project Teams

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Environment, Rural Development and Disaster Risk Management

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Disaster and Climate Change

Risk Assessment Methodology for IDB Projects

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1.
Organization of the Methodology

1. Organization of the Methodology

The Methodology consists of an introduction, a conceptual framework, three phases, concluding remarks, references, and 11 appendices. Specifically, it is organized as follows:

2. Introduction
3. Conceptual Framework for the Disaster and Climate Change Risk Methodology
4. Phase I - Screening and Classification
5. Phase II - Qualitative Assessment
6. Phase III - Quantitative Assessment
7. Concluding Remarks
8. References

Appendix A: Acronyms

Appendix B: Definitions

Appendix C: Hazard maps of the screening GIS support tool

Appendix D: Hazard modeling

Appendix E: Climate Change

Appendix F: Vulnerability modeling

Appendix G: Common mitigation measures

Appendix H: Ex-ante economic viability analysis

Appendix I: Terms of Reference

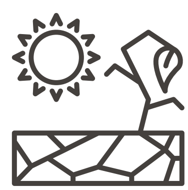
Appendix J: Disaster Risk Management for Multiple Works Operations

Appendix K: Green Infrastructure for Drainage Examples

This Methodology is organized around five steps—hazard exposure, criticality and vulnerability, simplified qualitative analysis, complete qualitative analysis, and quantitative analysis—which are grouped into three phases—screening and classification, qualitative assessment, and quantitative assessment. Each step includes text and graphics that describe the risk assessment steps, instructions to support them, and examples of project types. A summary of the natural hazards and project types included in this guide is provided below.

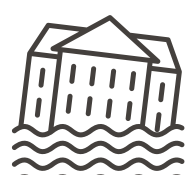
1.1 Natural Hazards

This guide focuses on 11 typical natural hazards that occur most frequently in the Latin America and the Caribbean (LAC) region, although it can also be applied to other natural hazards as needed. Hazard-specific icons are used throughout the guide where information and instructions for the specific natural hazard appears. The hazard icons are introduced below. Although sea-level rise is listed as a separate hazard, for the purposes of the Methodology it is assessed as a climate change parameter which exacerbates coastal hazards.

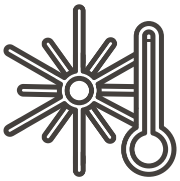


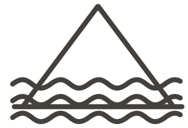
Drought

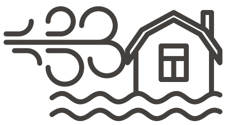
Earthquake



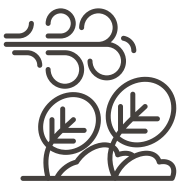
Flood


Heat Wave

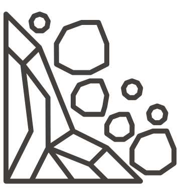

Sea Level Rise


Hurricane Surge


Tsunami


Hurricane Wind


Volcano


Landslide

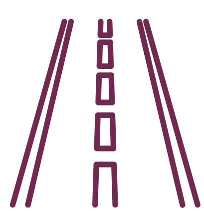

Wildfire

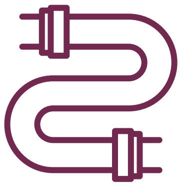
1.2 Project Types

The Methodology presents six project types that together constitute a robust reference for project-specific considerations, including tools, approaches, and mitigation measures. These project types are water utility, wastewater utility, drainage infrastructure, transportation infrastructure (roads, including bridges and tunnels), hydropower infrastructure, and social infrastructure (health care facilities and schools). They were identified as the most relevant for inclusion based on their recurrence in the Inter-American Development Bank (IDB) investment portfolio.

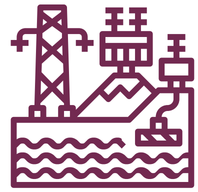
Reference material for each project type has been included to promote broader implementation and more consistent application of the Methodology. The informational icons below will help the reader easily navigate to the project type of interest.


Water Utility

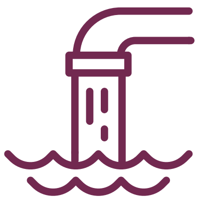

Road



Wastewater Utility



Hydropower Infrastructure



Drainage

Social Facility

1.3 Information Presented in this Report

The information included in the Methodology was developed by senior engineers and experts. In most cases, the information is drawn from internationally accepted best practices and is based on best professional judgement. The Methodology enables users to integrate project and site-specific conditions, as well as additional technical expertise. It is not intended to be the sole source of information to make design or other important project decisions.

The effects of climate change and disasters

2.
Introduction

2. Introduction

triggered by natural hazards pose a significant threat to sustainable development in the Latin America and the Caribbean (LAC) region. According to the Bank's document entitled What is Sustainable Infrastructure? A Framework to Guide Sustainability Across the Project Cycle (IDB and IDB Invest, 2018), the LAC region is among the most vulnerable to the impacts of a changing climate. In 2017, for example, floods in Peru resulted in losses of US$3.1 billion, and floods in Colombia resulted in 329 fatalities (Munich RE, 2017). If climate change is considered, damages may cost the region US$100 billion a year by 2050. Similarly, geophysical disasters have taken a heavy toll in the region. For example, the earthquakes in Chile and Haiti in 2010 caused US$30.8 billion in direct and indirect losses and approximately 521 fatalities, and US$7.8 billion in direct and indirect losses and 150,000–230,000 fatalities (estimated), respectively (GEM, n.d.).

Taking disaster and climate change risks into consideration in the design and construction of projects is important to increase their resilience. The Bank has developed a methodology to facilitate the identification and assessment of disaster and climate change risks and resilience opportunities in all relevant projects in the identification, preparation, and implementation phases. This provides a valuable opportunity to align existing policies, procedures, and methodologies to generate tangible benefit for the Banks' client countries, beneficiaries, and end users, as well as potential private investors.

Rooted in the existing Disaster Risk Management Policy (IDB, 2007) and Guidelines (IDB, 2008),[1] the Methodology builds upon and strengthens the current screening process and provides guidance for project teams to conduct disaster and climate change risk assessments in relevant operations, adding value to projects. While it is intended to have broader applicability, the Methodology is particularly relevant for projects with infrastructure components and is aligned with the Bahamas Resolution of 2016 (IDB, 2016) and the Bank's Sustainable Infrastructure for Competitiveness and Inclusive Growth Strategy – the Sustainable Infrastructure Strategy (IDB, 2013).

In the Bahamas Resolution, the Bank's Board of Governors welcomed Management's objective to improve the assessment of climate risk and identify opportunities for resilience and adaptation measures at the project concept stage. The Sustainable Infrastructure Strategy states that providing access to transport, electricity, water, and sanitation services improves quality of life through its direct impact on health, education, and economic opportunities. In addition, the Bank's Sustainable Infrastructure Framework[2] (IDB and IDB Invest, 2018) includes resilience in its definition of sustainable infrastructure.

1 The IDB Group is currently updating all of its policies, including the Disaster Risk Management Policy OP-704.

2 This Framework forms the basis of the IDB Group's definition of sustainable infrastructure and serves to support planning, designing, and financing of infrastructure that is economically, financially, socially, environmentally, and institutionally sustainable. The Framework presents four main principles of sustainability and proposes a menu of over 60 criteria that are key to operationalizing sustainability. It helps to identify key actions across the project cycle that can ensure sustainable infrastructure, from strategies and planning to portfolio and project design, construction, operation, maintenance, and decommissioning.

It emphasizes that sustainable infrastructure projects are (or should be) sited and designed to ensure resilience to climate and disaster risks.[3] Hence, by promoting resilience in projects, the Bank is furthering its commitment to improving lives in the LAC region.

The Methodology is aligned with the cross-cutting theme of climate change and environmental sustainability and the productivity and innovation development challenge of the Update to the Bank's Institutional Strategy 2010-2020 (AB-3008), with the IDBG Climate Change Action Plan 2016-2020 (GN 2848-4) and the Climate Change Sector Framework Document (IDB, 2015).

To test and validate its concepts and approach, the Methodology was piloted through the analysis and completion of risk assessments in 17 Bank-financed projects in preparation and/or execution from 2016 to 2018. This was instrumental in fueling the process.[4] Furthermore, the lessons learned from a close review of the disaster and climate change risk assessments conducted to date have provided valuable contributions to the Methodology. Two of the key lessons learned are the importance of supplementing hazard and climate change information with project vulnerability and criticality data, and the need for risk assessments to include qualitative as well as quantitative approaches.

While the Methodology was elaborated by specialists of the Climate Change and Sustainability Division (CSD/CCS), the Environment, Rural Development and Disaster Risk Management Division (CSD/ RND), and the Environmental and Social Safeguards Unit (VPS/ESG), collaboration with various sectors has been critical throughout the piloting and development phases.

This document breaks down the steps and explains different types of hazards, as well as sector- and structure-specific issues that need to be addressed. It is meant to provide practical support to project teams in different sectors, executing agencies, technical experts, and external consulting and design firms on how to integrate disaster and climate change risk considerations into project preparation and implementation, where relevant.

2.1 Background and Context

The impacts of disaster and climate change risk are becoming increasingly concerning because they reduce the predictability of future infrastructure needs and increase the vulnerability of populations and assets (Reyer et al., 2017). As part of sustainable planning, development projects should consider current and future risk and resilience opportunities in the design, construction, and operational phases (IDB and IDB Invest, 2018).

In 2007, the Bank incorporated disaster risk (including hazards emanating from climate variations) into the project cycle as part of the Disaster Risk Management (DRM) Policy (OP-

3 The IDB Group defines sustainable infrastructure as follows: "Sustainable infrastructure refers to infrastructure projects that are planned, designed, constructed, operated, and decommissioned in a manner to ensure economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire life cycle of the project." Disaster and climate change risk is embedded in the environmental sustainability (including climate resilience) principle for project preparation and design, which includes the following sustainability criteria: (i) assessment of climate risks and project-resilient design, and (ii) project design and systems optimization for disaster risk management.

4 The following activities have been conducted: (i) analysis of disaster and climate change risk assessments or equivalent elaborated for projects from 2016 to 2017; (ii) focused meetings with sector specialists to arrive at vulnerability and criticality aspects of projects in respective subsectors; (iii) elaboration of proposed methodology, including peer review; (iv) piloting phases of the methodology in IDB projects with a high or moderate disaster risk classification in preparation or with relevant disaster and climate change risk aspects during supervision covering the countries of Argentina, Brazil, Chile, the Dominican Republic, Ecuador, Haiti, Paraguay, Panama, and Suriname and the sectors of transport, water and sanitation, urban development, energy, agriculture and tourism; and (v) capacity building of sector specialists on disaster and climate change risk assessment. The piloting consisted of providing support in different forms: for some projects, a stand-alone Disaster Risk Assessment was conducted, for others, Disaster Risk Assessment-equivalent analyses were performed as part of the Environmental and Social Impact Assessment, for others, climate risk considerations have been included in a Climate Change annex of the POD; for others, specific technical accompaniment has been provided directly to design firms; and for others, technical site inspections have been carried out to evaluate pressing situations.

704) – Directive A2 – Risk and Project Viability,[5] to provide guidance to project teams in Bank-financed public and private sector projects. The DRM Policy Guidelines (GN-2354-11) of 2008 define a procedure to assess project disaster risk that includes: (i) project screening and classification integrated into the safeguards system (policy filter and screening form); and (ii) a disaster risk assessment (DRA) and a disaster risk management plan (DRMP) if the project is classified as high risk, or a more limited DRA if the project is rated as moderate risk.

The DRM Policy Guidelines explicitly mention climate change. The Natural Hazards and Climate Change section states that the Guidelines apply to all natural hazards, including hydrometeorological hazards—windstorms, floods, and droughts—which are associated with both existing climate variability and the expected changes in long-term climate conditions. It states that climate change is expected to alter some countries' disaster risk (i.e., their probable damages and losses) by changing the characteristics of hydrometeorological hazards. It also estimates that climate change is likely to influence weather-related hazards, and thus probable losses, in three principal ways: (i) by altering the intensity and frequency of extreme climatic events, such as hurricanes, tropical storms, droughts, heat waves and cold snaps; (ii) by shifting the average weather conditions and climate variability, such as precipitation levels; and (iii) by originating hazards that might be new to a certain region, such as sea-level rise and glacial melt, which can worsen storm surge and coastal flooding, as well as floods and droughts in watersheds.

In 2016, the IDB established a Community of Practice on Resilience (CPR).[6] The CPR is currently led by specialists of the Environment, Rural Development and Disaster Risk Management Division (CSD/RND), the Climate Change and Sustainability Division (CSD/CCS), and the Environmental and Social Safeguards Unit (VPS/ESG). It is open to participation by other divisions and aims to mainstream resilience across sectors and projects within the IDB. The objectives of the CPR are (i) to contribute to a better understanding of the factors that determine resilience and, thus, the sustainability of programs that promote the development of the LAC region; (ii) to harness existing knowledge and lessons learned to improve the resilience of IDB-financed projects; and (iii) to strengthen the Bank's and its clients' capacities to mainstream resilience into development programs.

To achieve these objectives, and in line with the Bank's international commitments on resilience, the CPR has proposed a three-year Work Plan focused on formulating a methodology proposal that can serve as a resource to (i) implement the A2 Directive of the OP-704 Disaster Risk Management Policy related to the integration of disaster risk assessments (including climate change) in Bank-financed operations and (ii) achieve IDB Management's objective of improving the assessment of climate risks and the identification of opportunities for resilience and adaptation measures at the project concept stage (Bahamas Resolution). The CPR has been working with focal points and focus groups across the IDB Group to gather sector knowledge and propose an approach that is relevant to the different sectors. As a result of this consultative process, the Disaster and Climate Change Risk Assessment Methodology was jointly crafted in 2017 and fine-tuned through pilot projects during 2018.

5 In the Identification and Reduction of Project Risk section, Policy Directive A-2 on Risk and Project Viability points out that "Bank-financed public and private sector projects will include the necessary measures to reduce disaster risk to acceptable levels as determined by the Bank on the basis of generally accepted standards and practices. The Bank will not finance projects that, according to its analysis, would increase the threat of loss of human life, significant human injuries, severe economic disruption, or significant damage related to natural hazards."

6 The CPR had been holding informal meetings since 2012. Prior the development of this methodology, other Technical Notes were published, including "Addressing Climate Change within Disaster Risk Management: A Practical Guide for IDB Project Preparation," 2015, and, previously, "Climate Change Data and Risk Assessment Methodologies for the Caribbean," 2014. This document includes some of the findings of those publications and proposes new actions based on a review of current practice.

This Methodology is in line with the disaster and climate change risk assessment approaches adopted by other multilateral development banks (WRI, 2018). These efforts also include the formulation of resilience indicators that can feed into a project's results matrix. The Climate Change Division, in cooperation with a group of sectors within the Bank, is currently developing a conceptual Resilience Framework for operationalizing climate resilience at the project and sector levels. The Bank aims to apply this Methodology in projects in 2019.

2.2 Objective and Audience

How should a project screen for and assess disaster and climate change risk? Once risks have been identified during the screening phase, what are the next steps in their analysis? Why should we care? (see Box 2.1). How should disaster and climate change risk be integrated at different project stages? The objective of the proposed Methodology is to provide a technically and operationally robust framework that answers these questions and serves as guidance for assessing disaster and climate change risk in projects.

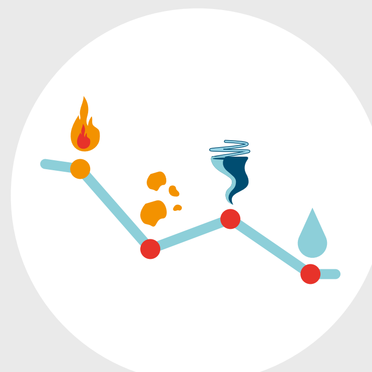
Box 2.1. Why should we care?

Exposure is widespread

The LAC region is exposed to several natural hazards, and their impacts have already been felt. In 2017, a variety of events, including landslides in Colombia, floods in Peru, earthquakes in Mexico, hurricanes in the Caribbean region, and wildfires in Chile, among others, adversely affected the region, leaving thousands of casualties and incalculable damages.

Human and economic losses hinder development

Although the most severe impact of a disaster is the number of fatalities, physical losses are also extremely important because they affect connectivity, basic services, and facilities, such as hospitals, schools and other critical infrastructure. In the worst-case scenario, they could eventually result in indirect fatalities. Inoperative infrastructure as a result of an event also impair national and regional economic development in the medium and long term. Disasters disproportionately affect people living in poverty and destroy productive capacity, which results in diminished labor productivity and demand for labor, decreasing employment levels and exacerbating the cycle of poverty in the short term.



Achievement of project objectives is compromised

Disregarding disaster and climate change risk during project preparation, design, and implementation increases exposure and vulnerability to natural hazards and could hinder the achievement of project objectives. It might shorten a project's lifespan or result in economic losses, as well as incremental economic costs for a country given the ongoing investments required to repair structures or replace them.

To reduce disaster and climate change risk in its projects, the IDB is committed to systematically integrating these considerations across its portfolio by assessing these risks throughout the project cycle. This will enable project teams to implement any adaptation measures necessary to address them.

2.2.1 Audience

This Methodology is intended as a practical resource that team leaders across sectors, executing agencies, technical experts, and external consulting and design firms can use to integrate disaster and climate change risk considerations at the project preparation and implementation phases as needed.

2.2.2 Scope of application

Risk assessments are by nature solution oriented. They seek to find the most appropriate measures to reduce and/or manage risks. They provide an assessment that enables resilience opportunities to be identified. Conducting a disaster and climate change risk screening and assessment process is one of several approaches used by the Bank to reduce risk and increase resilience. Other approaches include (i) production of disaster and climate change risk management knowledge through country risk assessments, climate change country profiles, and indicators such as the Index of Governance and Public Policy in Disaster Risk Management; (ii) advising on country programming; (iii) emergency response operations and post-disaster rehabilitation projects; (iv) preparation and execution of reconstruction projects, including loan reformulation; (v) policy reforms for strengthening DRM regulatory framework through policy based loans; (vi) financial protection instruments, such as parametric contingent credit facilities; and (vii) mainstreaming disaster and climate change risk management directly into sector projects.

This Methodology applies primarily to projects with infrastructure components at the preparation stage, across a variety of sectors financed by the IDB.[7] It can be used to help projects comply with the Disaster Risk Management Policy, to support the mainstreaming of resilience efforts, and as a good practice for project teams. It was conceived and designed for medium to large projects (both single structures and systems), including in urban settings. It is a living document that will continually be updated as new data and methods emerge in disaster and climate change risk management. The CPR is available to provide comprehensive support to project teams, including preparation of terms of reference and supervision of studies.

2.3 Disaster and Climate Change Risk Overview

According to the United Nations Office for Disaster Risk Reduction, disaster risk is defined as "the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined (...) as a function of hazard, exposure, vulnerability and capacity" (UNDRR, 2017: 14). In other words, disaster risk is a possibility that exists only at the intersection of its three components, and it cannot be described by any one of these factors alone (Figure 2.1).

7 For multiple-works operations, three main concepts should be applied: (i) the entire program should be classified based on a project sample; (ii) the sample may require a DRA, if applicable, and (iii) a Disaster Risk Framework should be established for the entire program, commensurate with the risk classification, following this methodology. See Appendix J for more details.

Figure 21. The Composition of Disaster and Climate Change Risk

The hazard component in the context of this Methodology refers to events originating in nature that pose a threat to population or property and that could thus cause damage, economic losses, injuries, or loss of life.[8] The Methodology considers both geophysical hazards—earthquakes, landslides, volcanic eruptions and tsunamis—and climate-related hazards, including wildfires, hurricanes, floods (inland and coastal), heatwaves, and drought.

The exposure component refers to the coincidence in space and time of people or assets (both physical and environmental) and threats posed by natural hazards. Hence, communities (Hallegatte et al., 2017), assets, services, or populations that are located within the area of influence of natural hazards are said to be exposed to these hazards and to potentially suffer damages.

The vulnerability component refers to the susceptibility of an entity to be harmed or damaged. For assets, systems, and people, it is their intrinsic individual and aggregated characteristics that give them an inherent proneness (or conversely, a resistance) to suffer harm. Here, vulnerability is defined in terms of the potential of being affected by natural hazards only. An additional dimension that characterizes vulnerability that might be useful to consider concerns the ability of a system, asset, or people/community to recover after having experienced a disaster. In the longer term, adaptive capacity, or the ability to learn from an experienced event, can be extremely beneficial. Finally, disasters are the materialization, or the consequence, of risk; the absence of disasters does not imply a corresponding absence of risk.

8 Man-made hazards are beyond the scope of this Methodology, including technological hazards or others caused by human activity, such as epidemics/pandemics, hazards caused by social and political violence (i.e., conflict-driven hazards), and financial shocks.

Box 2.2. Where does climate change fit into disaster risk?

As stated by the Intergovernmental Panel on Climate Change (IPCC) in its special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (IPCC, 2012), climate change refers to a lasting modification of the state of climate that "may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use." This definition is pertinent in the context of this document, as the focus on climate change in this Methodology is not on investigating its drivers and causes, but rather on examining the effects of climate alteration (regardless of its origin) on existing conditions, particularly with respect to disaster risk.

Depending on the time and scale of interest, an important distinction must be made between natural climate variability and overall forced climate change. Climate change is generally characterized along a set of emission or future radiative-forcing scenarios. They represent different possible pathways that the climate system might follow. The objective of these pathways is primarily to illustrate (and distinguish) the direction and magnitude of the expected mean changes associated with each scenario, and to provide a range of uncertainty around that projected path. One element of the uncertainty arises from differences between models in how they project the magnitude and spatial extent of the induced changes. A second and equally important part of that uncertainty arises from natural climate variability that reflects the weather aspect of the climate system, which is the day-to-day (random) noise of weather at any location around the world that fluctuates around the climatological mean. It is important to recognize that at regional and local scales, this noise dominates the day-to-day variability and can also surpass the expected climate change signal for many years to come when magnitudes of forcing are still relatively small and when the Earth system response did not have time to fully develop.

Despite the strong links between disaster risk and climate change science and adaptation, there has been a misperception that these are unrelated disciplines, mainly because climate change also includes climate mitigation (emission reduction) issues and because disaster risk also addresses geophysical risk. However, natural variability creates a critical link between the two, at least in the near term. While excursions away from the overall means are often the underpinnings of disaster risk, in future climate risk it is actually that natural variability superposed on a changing background that first causes significant impacts, often much before any altered mean climate conditions impose new threats. In fact, the most immediate changes in terms of climate risk might be visible in the extremes, such as extreme heat, storm intensity, and rainfall, which directly respond to altered surface and atmospheric temperatures. This recognition has gradually reduced the separation between disaster and climate change risk perspectives. Climate change adaptation has gained more prominence as governments and institutions have realized that the world needs to adapt to changes in climate. Recognition by both the IPCC and the UNDRR of this intersection of disaster risk and climate change adaptation resulted in the report entitled Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012).

In contrast to the rapid-response hazards from climate change that are related to surface and air temperature changes, other aspects of the climate system are changing more slowly. Changes in soils or vegetation or reductions in the cryosphere (snow and ice) take more time. One of the slowest signals of climate change is sea-level rise. It involves the physical process of increasing the heat content in the world's oceans through mixing down of warmer surface waters, leading to thermal expansion of the water in deeper layers of the ocean. An additional contribution comes from the melting of ice in high mountain and polar environments, leading to a higher freshwater flux into the oceans. The time scales involved in the sea level adjusting completely to a warmer world will go into many centuries and millennia. Overall, it is important to recognize that the effects of climate change will evolve over time, with some responses being directly tied to changes in atmospheric composition, to radiative forcing and thus particularly to surface temperature change (rapid-onset hazards), while others can take more or substantially more time to materialize as changes in known hazards (slow-onset hazards). The former are difficult to dissociate from even "present-day" disaster risk, while the latter are the creeping effects of global climate change.

Hence, the influence of climate change on disaster risk is what this Methodology calls climate change risk. This translates mainly into adding a component of change and variability (and uncertainty) to the otherwise stationary treatment of hydrometeorological-related hazards (in the future) in disaster risk. In a way, climate change may be considered a disaster risk modification—and possibly exacerbation—factor.

Disaster and climate change risk, in the context of this Methodology, is thus the result of the simultaneous existence of a hazard (influenced by both slow and rapid onset impacts of climate change, if applicable) and an asset or population that is not only exposed to this hazard, but also vulnerable to be damaged by it.

2.3.1 What is a disaster risk assessment at the project level?

A DRA in the context of this Methodology refers is an evaluation of the disaster and climate change risks for a particular project (see Guidelines paragraph 3.17 for the full definition of DRA).[9] Following the definition of disaster and climate change risk discussed above, a DRA is thus a "qualitative or quantitative approach to determine the nature and extent of disaster risk by analyzing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihood and the environment" (UNDDR, 2017: 15). For the purposes of this Methodology, the DRA includes a disaster and climate change risk management plan (DRMP), which includes specific measures to be implemented to reduce the risk identified in the assessment.

2.4 Diagnosis of Current Practice

The Disaster Risk Management Policy approved in 2007 and its corresponding Guidelines of 2008 constitute an important conceptual and operational framework that represents a commitment to a modern way to conceive, design, and implement projects. The piloting of disaster and climate change risk assessments in projects under this framework has resulted in several findings and lessons learned (Table 2.1) that are worth highlighting, as they inform the Methodology. The Methodology also incorporates significant advances in the analysis of disaster and climate change risk in the last 10 years. It provides additional support to project teams in applying the Policy and its Guidelines.

9 For the purposes of this document, the term DRA is used interchangeably with Natural Hazard Risk Assessment, Disaster Risk Assessment, and Disaster and Climate Change Risk Assessment. Likewise, the term DRMP is used interchangeably with Disaster Risk Management Plan and Disaster and Climate Change Risk Management Plan.

Table 2.1. Diagnosis and Solutions for the IDB DRA Practice

Finding	Lessons	Solutions
Inconsistent application of the Policy	Although the Disaster Risk Management Policy has existed for more than ten years, it has not always been consistently applied across the universe of operations backed by sovereign and non-sovereign guarantees throughout the project cycle.	The IDB has been working on a process to facilitate the application of the policy, pilot it in projects, and receive feedback from sectors. The proposed Methodology serves as a practical document for project teams to facilitate the consistent application of the policy.
Division of risk	Under Directive A.2 of the Disaster Risk Management Policy, there are two types of risk scenarios: **TYPE 1:** "The project is likely to be exposed to natural hazards due to its geographic location." **TYPE 2:** "The project itself has the potential to exacerbate hazard risk to human life, property, the environment or the project itself." In practice, this distinction poses challenges to those in charge of assessing and managing risks. According to the Policy Guidelines, the Type 2 risk scenario must be addressed under B.3 of the Environment and Safeguards Compliance Policy (OP-703).	Although the impacts from disaster and climate change risk on operations may lead to two types of consequences (impacts on the operation itself and its viability, and impacts on surrounding communities), from a technical standpoint, ideally risk must be analyzed as a whole. This Methodology has been designed to enable, in most cases a unified assessment of risk, and to generate outputs that are useful to all the actors involved, including the project team leaders and VPS/ESG specialists.*
Risk classification biased towards hazard	The hazard component has historically been given more weight than risk as a whole, without sufficient consideration of the vulnerability component. Moreover, screening is usually performed early in the project cycle, often with limited information about the details of the project. This has resulted in risk classifications that are biased toward hazard versus a more integrated understanding of risk.	To obtain a more balanced analysis, the Methodology proposes a second layer of classification, which consists of a preliminary vulnerability and criticality analysis of the operation. Additionally, the Methodology has a sequential, step-by-step approach, and vulnerability is assessed throughout the Methodology and corresponding project cycle stages.
Lack of methodological process in past DRAs	An analysis of past DRAs reveals that they lacked a consistent methodological process defining a standard, clear way to carry out these assessments. Thus, quality varied greatly, there was a strong disconnect between projects' specific characteristics and risk calculations, modelling efforts were not consistent with risk levels and project scope, and the recommendations and risk reduction measures proposed were too broad. Additionally, since a quantitative risk assessment is technically complex and expensive, and the risks to which a project may be exposed are numerous, the scope of this type of assessment needs to be narrowed.	The Methodology aims to close this gap by providing a robust process that clearly defines and compiles standard methods and techniques to carry out DRAs, offering various options according to project type, risk level, and the level of detail needed. The Methodology also includes a qualitative risk analysis to be conducted prior to a full quantitative risk assessment. It will serve as a filter to focus on the aspects that really require a quantitative treatment. The minimum criteria for undertaking a qualitative risk analysis are included in Step 3.

Finding	Lessons	Solutions
Climate change uncertainty	There are considerable uncertainties when it comes to incorporating climate change into the risk assessment at the project level.	The Methodology provides guidance to understand climate change concepts and includes techniques to incorporate climate change projections into disaster risk assessments.
Limited data availability in LAC countries	Conducting a quantitative risk assessment is fundamental to include disaster risk in the cost/benefit and project viability analyses, but the availability of information at the project level is a major challenge. Many countries in the LAC region have insufficient data to conduct quantitative assessments. Moreover, gathering the information necessary to carry out this type of assessment can be extremely expensive, or may extend beyond the project preparation period. This leads to burdensome studies that are not commensurate with the scope of the project or, conversely, to projects where no risk assessment is done at all because of a lack of information.	The Methodology proposes conducting a qualitative risk assessment that will serve as a basis for establishing the scope of a subsequent quantitative assessment, when necessary. It also provides guidance on how to carry out robust quantitative analyses that can be adapted to different conditions of information availability in projects. Furthermore, sensitivity analyses can be a less complex option that can supplement cost/benefit analyses in relevant projects.

**Note:* Should any of the impacts under Type 2 scenario be not included in the DRA, the Type 2 risk scenario could be addressed under the Environment and Safeguards Compliance Policy (OP-703).

3. Conceptual Framework for the Disaster and Climate Change Risk Assessment Methodology

2. Conceptual Framework for the Disaster and Climate Change Risk Assessment Methodology

3.1 Structure of the Methodology

The Methodology for the assessment and management of disaster and climate change risk in projects proposed in this document takes into consideration information at each project stage,[10] the variety of IDB-financed projects and operations, and the availability of information depending on the country and type of hazard.

The Methodology recognizes the uncertainty of climate change; that is, there is inherent uncertainty in future conditions, including those related to climate. Realizing that there is the risk of both over-engineering solutions (i.e., using costly methods or mitigation measures that are not necessarily appropriate) and not fully accounting for future conditions (i.e., not appropriately considering plausible future conditions that could impact investments), it integrates bottom-up approaches that are more likely to lead to a low-regrets solution where significant risks are addressed by strategies that are also likely to minimize costs and achieve co-benefits that will be valuable even if future climate differs from the central trend of model predictions. To do this, it is necessary to understand the weather and climate risk context and how it is likely to change. The result is a consistent and viable process that adds resilience, sustainability, and value to projects.

The fundamental principles that inspire this Methodology are:

- Compliance with the essential Policy mandate not to finance projects that increase social, economic, or environmental risk in absolute terms with respect to the baseline;

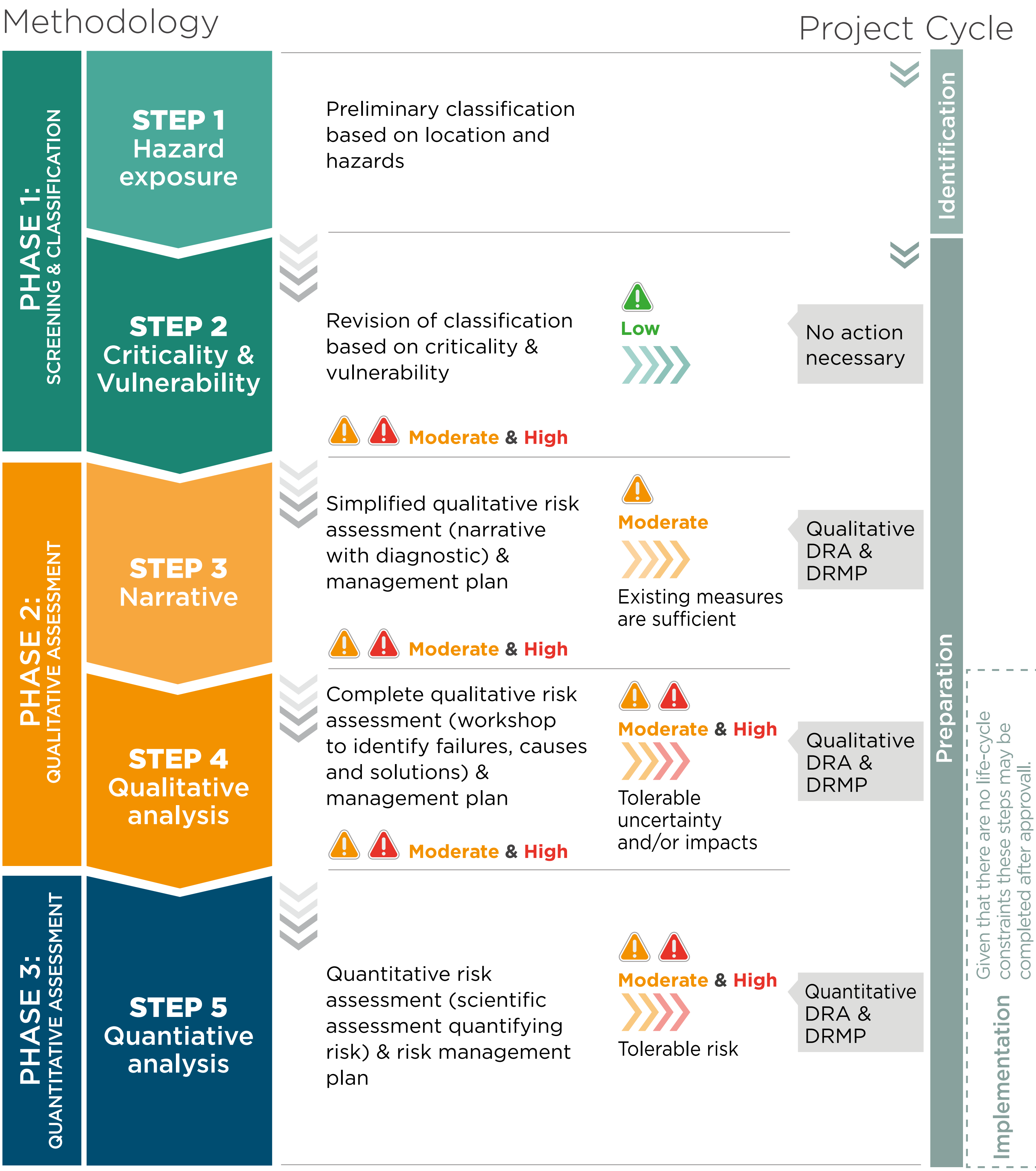
- Clarification of the implications of considering two types of risk scenarios (Type 1 and Type 2), aligning the provisions of the Disaster Risk Management Policy with processes, but considering the risk as a whole, for the analysis and assessment process; and

- Improvement of the processes and outputs that result from the screening and classification—the DRA and the DRMP—by strengthening the conceptual framework, making the process scalable, developing concrete tools and recommendations, and piloting the approach together with Bank sectors.

The Methodology involves several phases and steps where efforts and resources are commensurate with levels of risk, as shown in Figure 3.1.

10 The IDB project cycle is composed of four main stages: Identification, Preparation, Implementation and Closure, with an Approval milestone between the Preparation and Implementation phases. During the Identification phase, the project is first identified and the Project Profile (PP) is prepared; during the Preparation phase the project is further developed and the Proposal for Operations Development (POD) and the Draft Loan Proposal (DLP) are prepared; during the Approval the Loan Proposal (LP) is approved; during Implementation the project is monitored; and finally during Closure the project is finalized and the project evaluation is completed.

Figure 3.1. Disaster and Climate Change Risk Assessment Methodology



Notes: Should the assessment be carried out after board approval, a legal condition might be included in the loan contract for it to be conducted.

3.1.1 Phase 1: Screening and classification

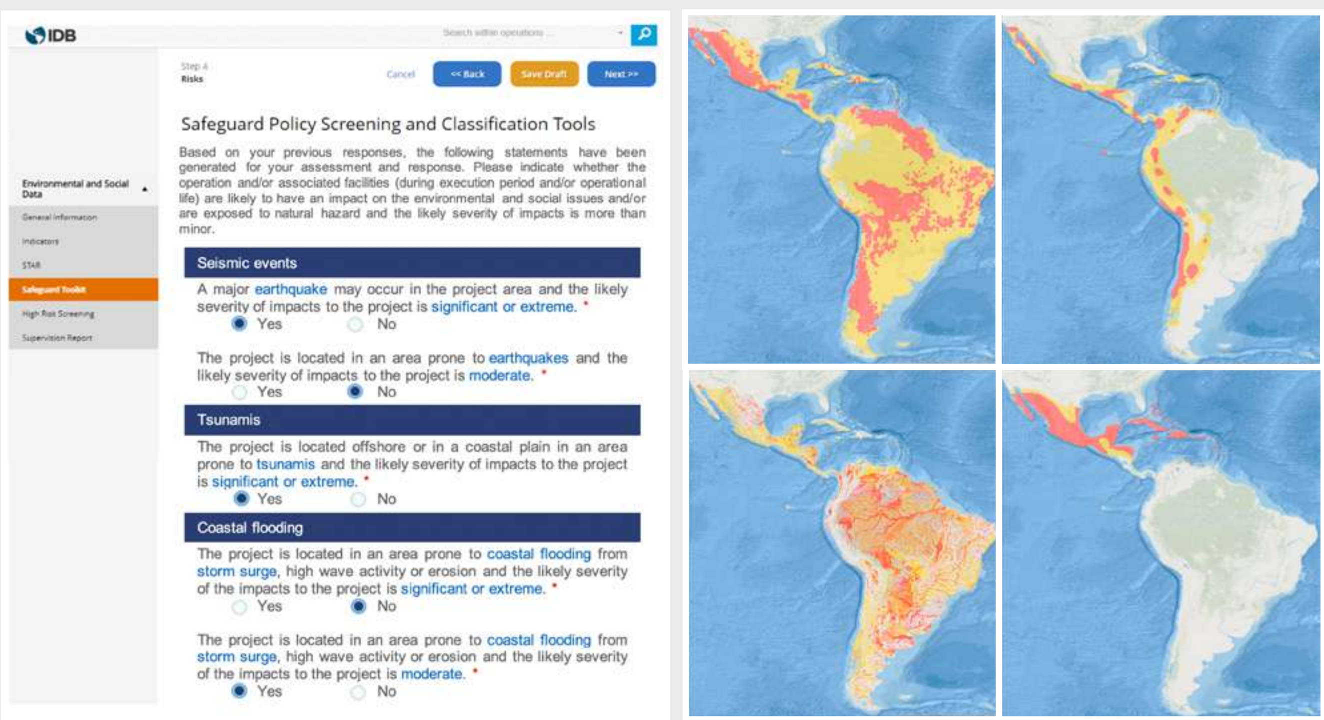
Phase 1 applies to all IDB projects and comprises two steps:

STEP 1: Preliminary classification based on location and hazards

The first step involves using the current Screening and Classification Toolkit[11] in the IDB's central operations management system (Convergence) (Box 3.1). IDB specialists use this toolkit to identify whether a project triggers the Disaster Risk Management Policy by considering the potential hazards that might affect the project. The toolkit is based on a series of project-specific questions and is supported by a geographic information system (GIS) platform to enable specialists to accurately fill it out. The outcome is an initial risk classification for the operation. This classification is included in the Safeguards Screening Form.

Box 3.1. Screening and Classification Toolkit

The Screening and Classification Toolkit automatically provides an initial Disaster and Climate Change Risk Classification for the operation, as either Low, Moderate or High-Risk, based on the answers to specific questions in the toolkit. The questions, which are embedded in the IDB's central operations management system, includes a link to a GIS platform which includes 21 hazard maps to help answer the questions on exposure to natural hazards. Of the 21 maps, 10 relate to natural hazards with no consideration of climate change, including geophysical hazards (**seismic, tsunami, landslide, wildfire, volcanic, hurricane wind, storm surge, riverine flooding, drought, and heatwave hazards**), and the remaining 11 relate to hydrometeorological hazards considering climate change (**sea level rise, drought, water scarcity, two heatwave projections, and five precipitation projections—all for the end of the century**).



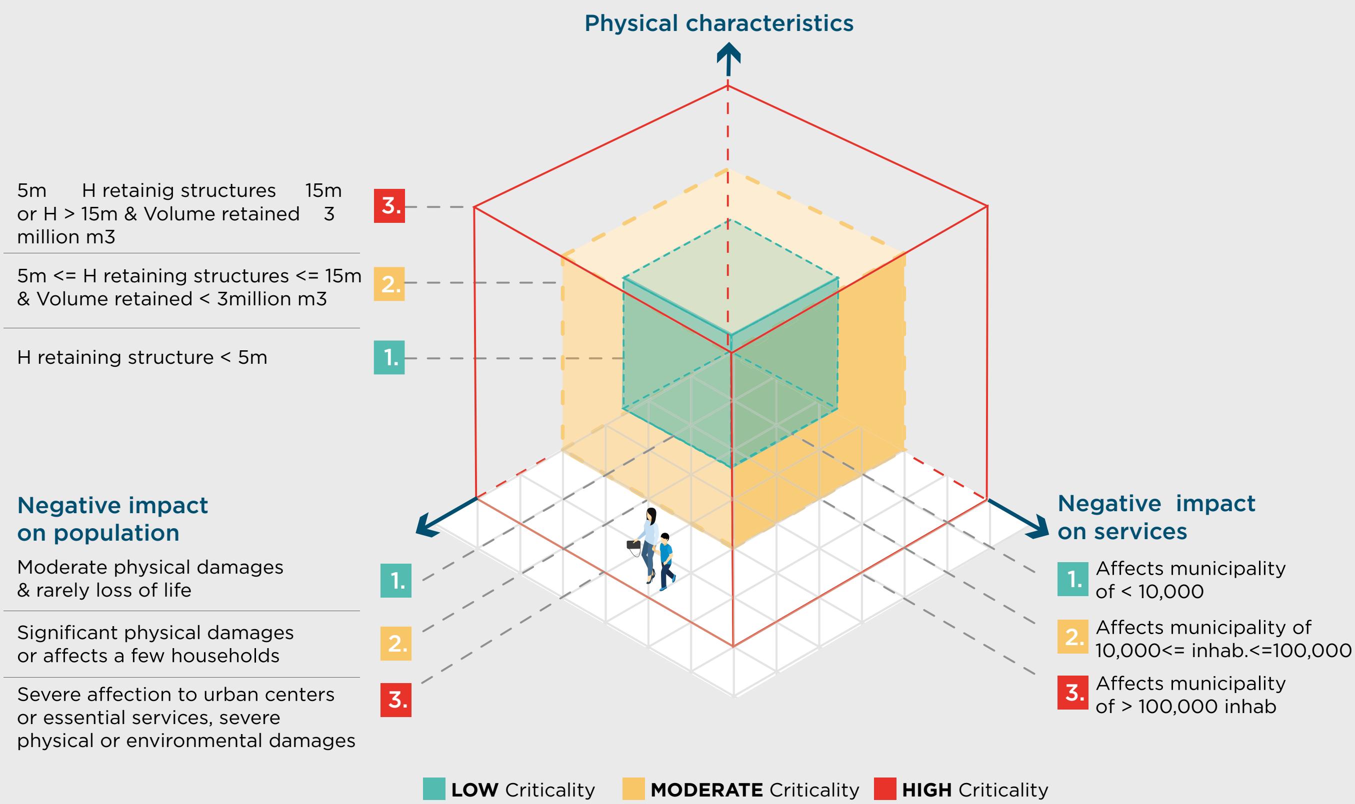
11 The questions related to disaster and climate change risk were included in the Screening and Classification Toolkit for the first time in 2012.

STEP 2: Revision of classification based on criticality and vulnerability

The second step in the Methodology is designed to reflect a project's criticality and vulnerability levels and to complement the result from the previous step to obtain a disaster and climate change risk classification that is representative of the operation itself and not merely of hazards. Vulnerability refers to the inherent qualities that determine a structure's (or a system's) susceptibility to suffer damage. Criticality refers to the degree of significance that a structure or system holds within a larger context due to the type and scale of services or functionality it provides. Both concepts lead to a better understanding of the potential consequences (physical negative effects on the structure and on population and services) that a failure of the operation due to natural hazards would create (Box 3.2). This step aims to help specialists better define the scope of the operation, identify critical project characteristics, complement the initial operation risk classification based on hazards, and decide (according to the resulting classification) if a further assessment of risk is needed.

Box 3.2. Project Criticality and Vulnerability

To facilitate the process of recognizing the features that make a structure or system more or less critical and vulnerable, general guiding questions concerning **physical characteristics, level of service provided, and magnitude of potential negative effects on third parties** are provided. In addition, three subsector-specific charts that illustrate this concept for roads, water and sanitation systems, and hydroelectric dams were developed in cooperation with sector specialists. These charts reflect the most universal and the technically pertinent attributes for each type of infrastructure that are the source of the sector's main concerns. The following chart is the example developed for hydroelectric dams.



As a result of this phase, projects are classified as low, moderate, or high risk (if as a result of Step 2 there is a new classification, the safeguards screening form needs to be updated accordingly). If an operation is categorized as low risk, it may exit the process at this point; all others must move to Phase 2.

3.1.2 Phase 2: Qualitative disaster and climate change risk assessment

This phase applies to all IDB projects classified as moderate or high risk and involves two steps. Certain projects classified as moderate risk may skip Step 4 and any further steps if Step 3 gathers sufficient information.

STEP 3: Simplified qualitative risk assessment (risk narrative) and risk management plan

The third step applies to all moderate- and high-risk (based on the results of the previous phase) projects and involves gathering all valuable data regarding studies, documents, and design considerations that may already exist for the operation, and information on adaptive capacity of the project or communities. The aim is to document how and to what extent thought has been given to disaster and climate change risk management issues (Box 3.3). This step also operates as a first filter to identify the moderate-risk operations that (along with high-risk operations) must move on to the following step, and those that may exit the process at this point because they have adequately proven, based on the evidence presented in the narrative, that risks have been sufficiently addressed.

Box 3.3. Disaster and Climate Change Risk Narrative

When gathering data and beginning to assess what risk considerations have been included in the design of an operation, questions should be asked at the level of the specific project and should be tailored to its circumstances. In general, these should address past event occurrences, existing studies, if and how specific hazards, climate change, and vulnerabilities have been (or are planned to be) assessed, and what gaps exist. The following is an example of questions for a road rehabilitation where mudslides, earthquakes, and landslides have been preliminarily identified as potential threats:

Existing studies

- Are there any previous risk studies for the existing assets? (Have the impacts from hazards on the operation, and those from the operation on the risk conditions in the area, been assessed?)

Hazard evaluation

- Have the local meteorology, hydrology, and climate change been studied, and how? (Are there gauge data? Have global/regional climate models been consulted? Are there official standards for the use of climate projections?) Have the existing climate projections been verified?
- Have the local geology and seismicity been characterized, and how? (Have the existing slopes been studied? Does the road cross active faults? It there a seismic catalogue for the area?)

Design considerations

- Has climate change been considered in the pavement design of the road, and how?
- What are the hydrologic and hydraulic parameters used for the designs of the bridges, culverts and longitudinal drainage? (Analysis methods, design return periods, flood frequency analysis, climate change)
- Have slope stabilization measures been studied for the mountainous section of the road?
- What seismic design standard has been used for the bridge design? (Is there a local design code?)

Response systems

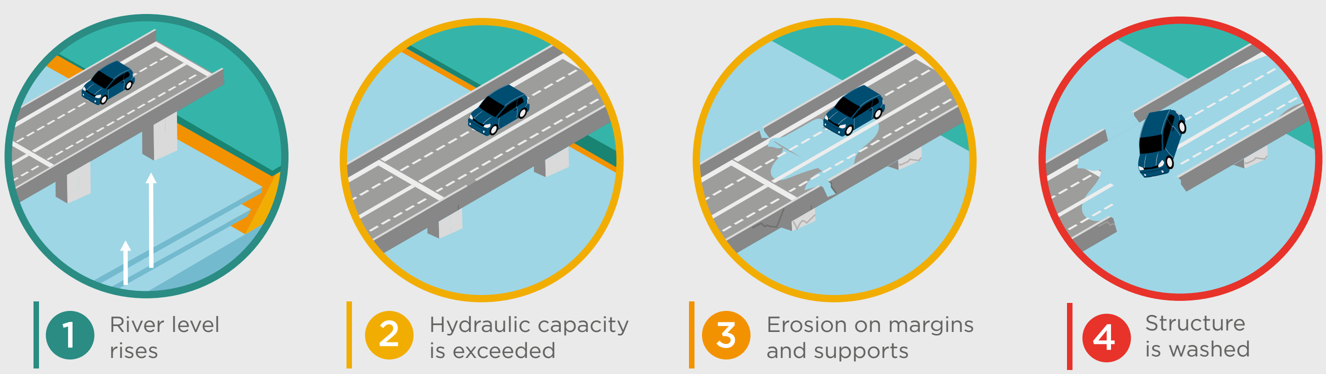
- Is there an early warning system in place in the city, or is one planned for mudslides and rains?
- Has a business continuity or contingency plan been developed to ensure the continuation/rapid recovery of the service provided? Is there redundancy?

STEP 4: Complete qualitative risk assessment and risk management plan

The fourth step involves performing a complete qualitative risk assessment and an accompanying disaster risk management plan for all high-risk projects, as well as for moderate-risk projects that were determined to need it in the previous step. This could involve, for instance, conducting a failure modes analysis with thematic and sector experts to qualitatively evaluate all the ways in which a project might fail as a consequence of the occurrence of a natural event, the causes of failure, and the consequences for both the structure and the surrounding environment and communities. It should include an estimation of the order of magnitude of the impacts that would not occur if the project was not conducted. By first conducting a qualitative assessment of all risks, it can be easily determined whether a detailed quantitative assessment is required and, if the answer is yes, the quantitative assessment can be properly targeted to only cover the specific parts of the operation and topics that actually require it. This step also includes a disaster and climate change risk management plan for those features of the operation that are deemed to not compromise its technical and/or economic viability. Those that may compromise the operation's viability must move on to Phase 3 (Box 3.4).

Box 3.4. Qualitative Disaster and Climate Change Risk Assessment

A qualitative assessment can be done through a workshop where disaster and climate change risk experts work with technical personnel from the design/construction firms and the operation's executing agency to **discuss and gauge all possible risks, contributing factors, potential consequences, and intervention measures.** Other qualitative techniques include formally using the Delphi method for consulting expert opinion—consensus building method of performing group surveys or interviews with a select panel of experts (Hallowell and Gambatese, 2010; Garson, 2012)--or using risk matrices that rate risks based on qualitative estimations of frequency and magnitude of impacts. In all cases, local professionals and technicians must be involved to ensure that local knowledge is mined. The following illustrations show a schematic mode of failure for a road identified through a failure-mode workshop, and its realization.



3.1.3 Phase 3: Quantitative disaster and climate change risk assessment

This applies to all specific features of an operation that require a quantitative assessment according to the results of STEP 4.

STEP 5: Quantitative risk assessment and risk management plan

The fifth step involves performing a quantitative risk assessment and accompanying DRMP for the high- or moderate-risk operations that were determined to need it in the previous steps (Box 3.5). This involves quantitatively modeling the aspects that can be tied to specific physical attributes, structures, modes of failure, or hazards that were found to require further investigation. It also entails scientifically and mathematically evaluating the vulnerability, hazard, and risk for those selected aspects for both the structure itself and the surrounding environment and communities, including an estimation of the impacts that would not occur if the project did not exist. An evaluation of risk tolerability and of technical and economic viability must also be performed to ensure compliance with the Bank's policy to not increase risk with respect to the current situation and follow the best tolerability standards of each subsector. The Methodology offers a range of methods, techniques, and models to calculate risk for both individual structures and systems according to types of hazards, structures, and level of detail required.

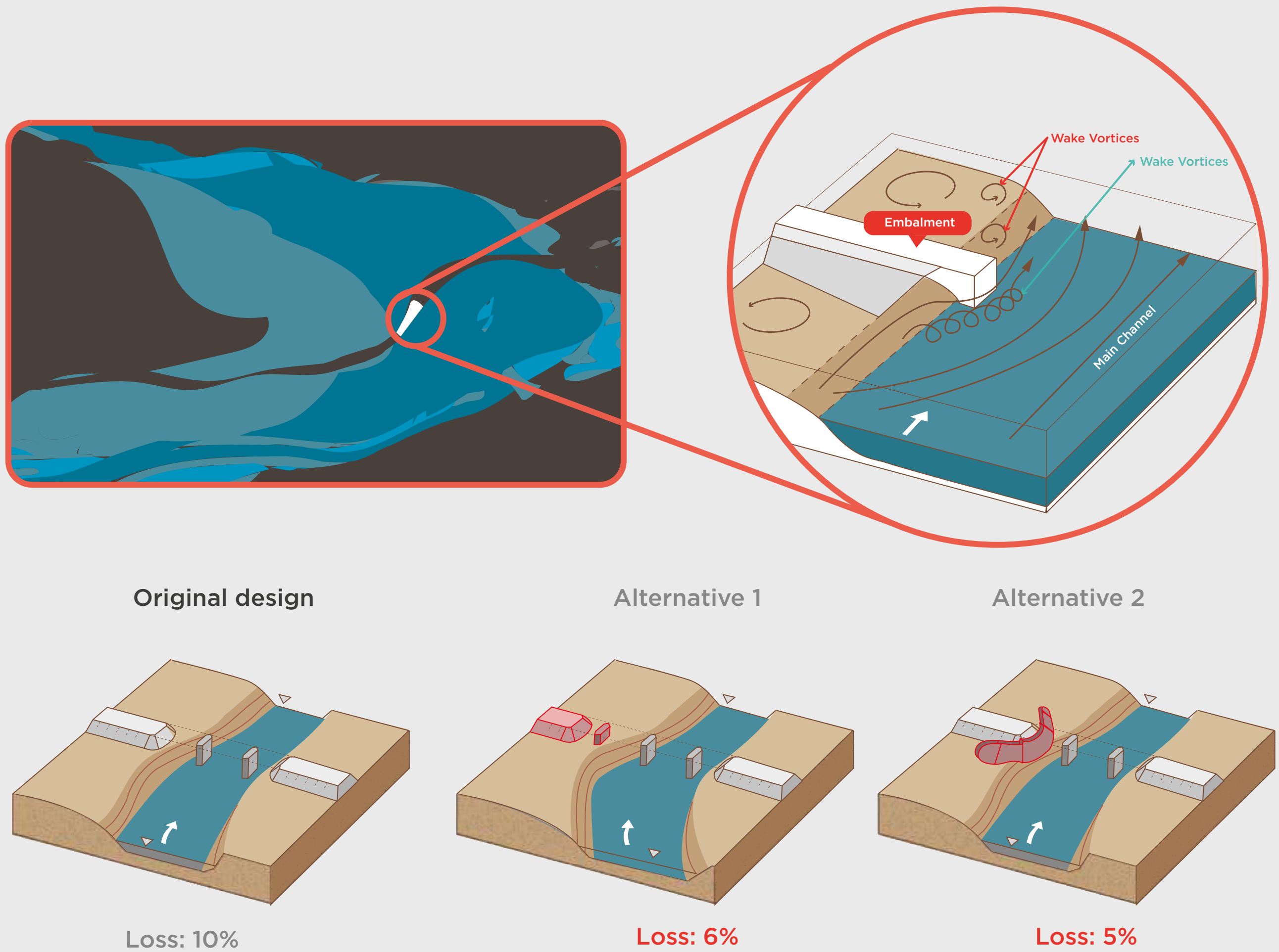
In addition to the above, innovative methods such as Robust Decision Making (RDM) for systems involving significant uncertainty are gaining increasing relevance. This method differs from standard cost-benefit analyses, which seek to predict the costs and benefits of a set of initial projects or project designs and then select the optimal option—all contingent on a thorough characterization of the uncertainties. Instead, RDM first uses simulation models to *stress test* one or a few select actions (policies and/or investments) across a large set of plausible futures (Groves and Lempert, 2007; Lempert et al., 2003; 2006) according to a list of several metrics for success. It has been widely used in the water sector in the last decade.

The DRMP is developed based on the findings of the quantitative risk assessment. This plan might include recommendations on (i) the design: gray measures (structural or engineering-based solutions) such as building retention ponds or other structures such as retaining walls, or green measures—ecosystem-based adaptation; (ii) construction: emergency response plan during construction works; and (iii) operation: measures related to changes in processes and procedures for the operation and maintenance of a project (e.g., adjust frequency of cleaning of drainage canal to ensure maximum capacity), business continuity and/or contingency planning, early warning systems, and financial protection schemes (including insurance); or it could be a hybrid combination of the aspects listed above. The measures set forth in the DRMP must include a cost-benefit indicator as well as the level or priority.

Box 3.5. Quantitative Disaster and Climate Change Risk Assessment

A quantitative risk assessment is a **mathematical and/or physical model** used to **quantify risk** in economic (**expected economic losses**) and human (affected, injured, and lives lost) terms (**expected economic losses**). Methods to assess risk range from simple deterministic methods (using single events) to fully probabilistic methods (where modeling is done following strict probability theory to obtain the full range of potential losses).[a] Intermediate options include deterministic methods, where one or more discrete hazard scenarios (may be simulated or historically recreated, such as design or worst-case scenarios, for example) are modeled, and vulnerability and expected losses are calculated for those scenarios. The following figures show a hypothetical example of a risk model and calculation (including modeling of the hazard and vulnerability) and the related quantitative evaluation of the proposed measures to reduce risk.

a An exposure assessment (where the vulnerability component is missing) is not a risk assessment. However, it is sometimes used as an indicative assessment or as an intermediate step in risk evaluation. In this assessment only the number of people and assets exposed to a hazard is calculated.



Source: Modified from Barkdoll et al. (2007)

3.2 Use of the Methodology

The Methodology applies mostly to projects in preparation across a variety of sectors financed by the IDB. It can be used to help project teams comply with the Disaster Risk Management Policy, to support the mainstreaming of resilience efforts, and as a good practice for project teams.

The Methodology is intended to serve first as a robust conceptual framework that merges both a technical and an operational logic, and second as a resource that specialists can use whenever they have an operation where the topic of disaster and climate change risk is important. It enables risk to be assessed both from a safeguards perspective (as projects need to comply with the policy) and a resilience perspective (seeking to improve projects and attain sustainability). Apart from supplementing the Disaster Risk Management Policy and its Guideline, this Methodology also provides an opportunity to incorporate disaster and climate change risk and resilience at the project design and implementation phases, thereby contributing to the development of sustainable infrastructure.

Early identification is essential for project teams to be able to effectively incorporate disaster and climate change risk reduction and resilience opportunities into project design. Furthermore, coordination among members of the project team, executing agencies, design/construction firms, and disaster risk management and climate change experts must be guaranteed so that these risks can be clearly identified from the beginning and at the moment of conducting DRAs. Coordination also helps determine how and what added value the DRA can provide to the project without duplicating analyses that may already be incorporated in design standards and codes, and it can focus the DRA on areas where traditional engineering has not yet reached. Including climate change risk considerations in the DRA, communicates that climate change has the potential to manifest itself in a change in the hazard and risk profiles. Because stationarity might not be a suitable foundation on which to base design standards and codes, an iterative revisiting of evolving conditions might be necessary to capture new types or ranges in magnitude of known hazards, and to assess the possibility of cascading effects.

Box 3.6. A Note on Introducing Disaster and Climate Change risk into Economic Viability Analyses

The IDB's project formulation process requires a cost-benefit analysis (CBA) to be carried out as an ex-ante economic analysis (conducted early on during project preparation) to evaluate economic viability[a]. Appendix H: Introducing Disaster and Climate Change Risk into Economic Viability Analyses proposes a way to incorporate the disaster and climate change dimension into the CBA analysis of a project. **This appendix is not a formal step of the DCCRA methodology** and should not be confused with other economic analyses conducted as part of the DCCRA.

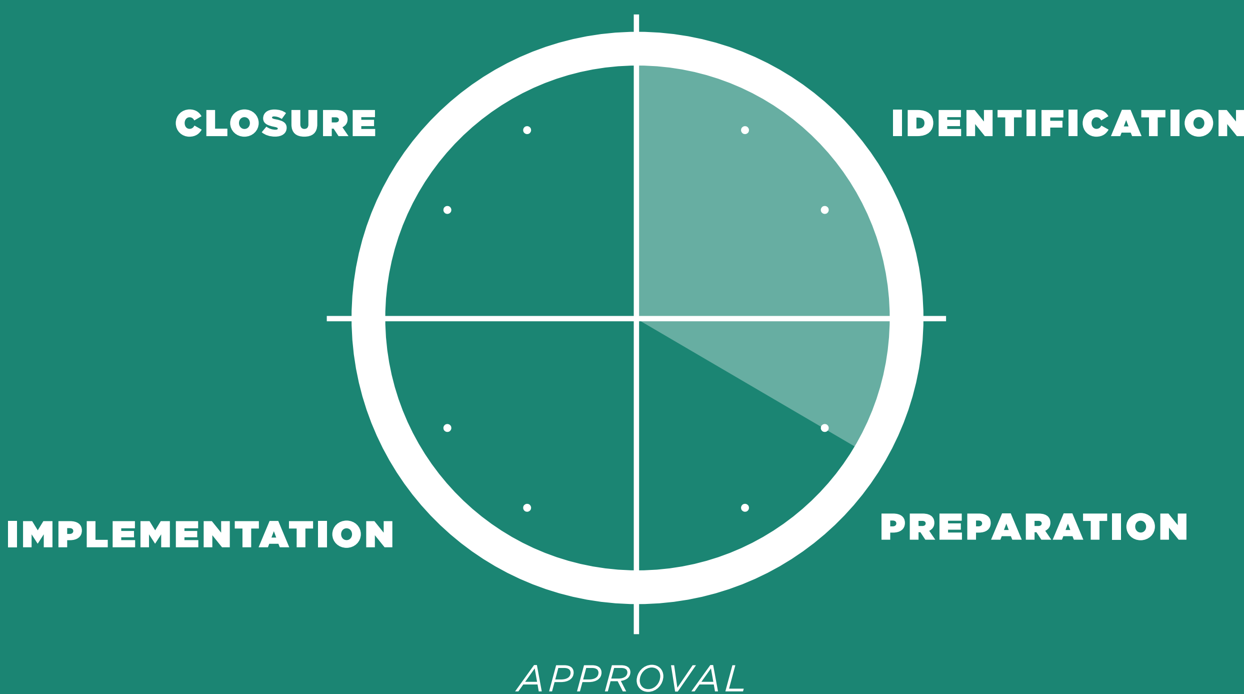
Appendix H is a simple and preliminary approach to this topic, which aims to begin a discussion with project economists and teams. The method is based on effects that a "worst case scenario" could have on expected economic returns (in the project's CBA) and the sensitivity of the net present value and internal rate of return to a disaster occurring when no detailed data and modeling are available. Despite the simplicity of the approach, this appendix provides initial inputs on ways that disaster and climate change might influence a project's economic viability study (namely, the CBA). The information coming from detailed analyses such as a DCCRA can be used to enrich the scenarios discussed, giving decision makers additional information on the disaster and climate change risk faced by a project in terms of expected benefits. Thus, if a project is able to obtain results from a quantitative risk assessment at the time when the ex-ante economic analysis is conducted, they can be used directly as inputs to this analysis instead of the considerations described in the appendix. In a world where disaster and climate change losses can jeopardize development gains and where a project's CBA is one of the most important tools used to make public investment decisions, disaster and climate change risk needs to be part of the discussion.

Source: Eduardo Zegarra, GRADE, economist consultant.

a Financial feasibility encompasses the availability of financing mechanisms, contingent credit line facilities, and the overall ability to generate sufficient income to meet debt commitments and operating payments. Economic feasibility is a more comprehensive concept that illustrates that a project's expected benefits exceed its estimated costs, allowing the use of social prices and other value adjustments to reflect positive or negative externalities.

4.
PHASE I: Screening & Classification

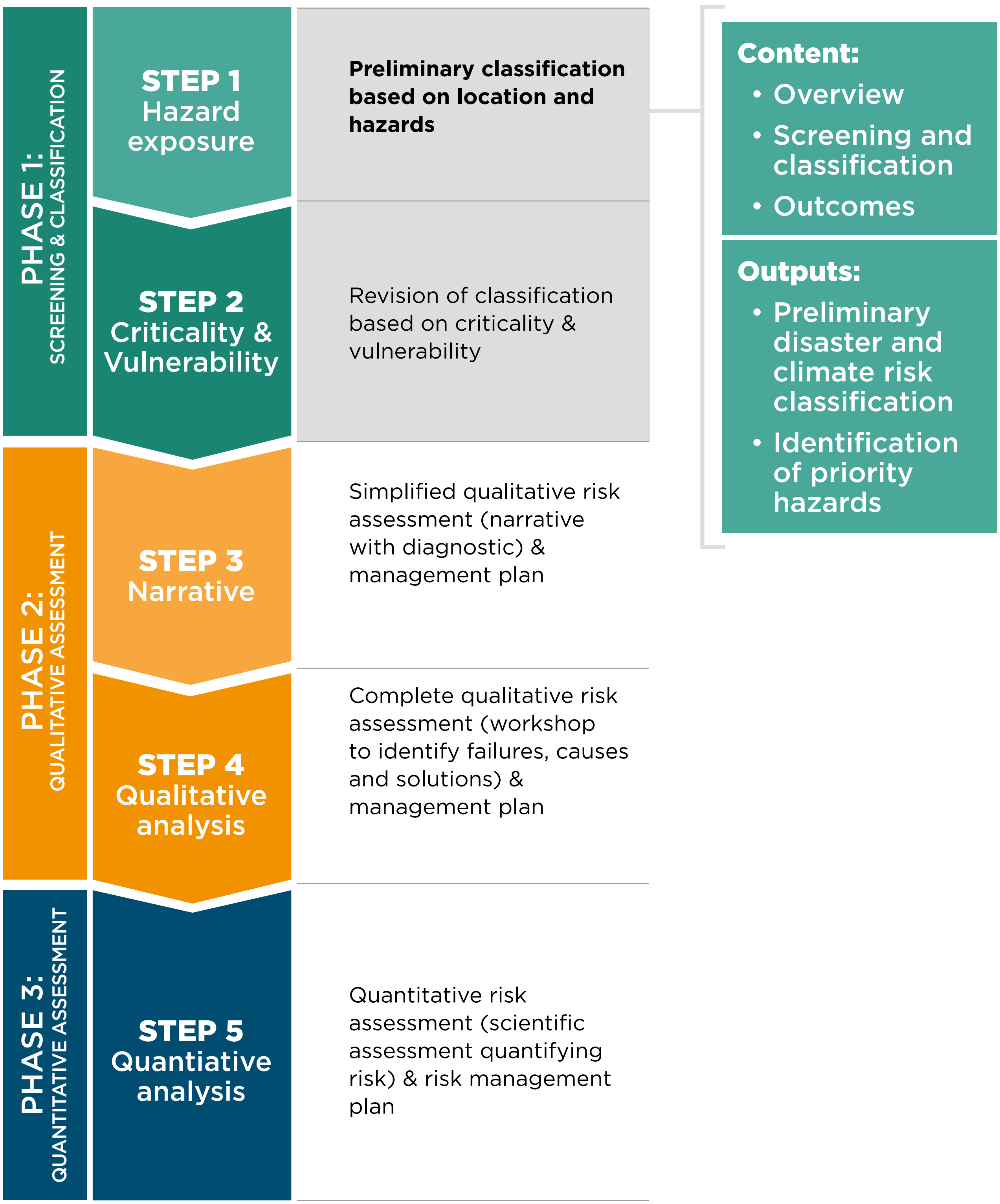
This phase should be conducted as early as possible in the project cycle, and no later than at the time of preparing the Project Profile, when there is a minimum definition of the operation and room for a general hazard and vulnerability/criticality screening. Usually, this occurs during the identification stage where the specific location, scope, and characteristics of the project are set.



4. PHASE I – SCREENING & CLASSIFICATION

4.1. Step 1: Preliminary Classification Based on Location and Hazards

Figure 4.1. Step 1



4.1.1 Overview

The objective of Step 1 is to use the Screening and Classification Toolkit created for the IDB's Environmental and Social Safeguards Unit (ESG) and interpret its output. IDB specialists use the Toolkit to determine whether a project triggers the Disaster Risk Management Policy—one of several policies included in the IDB Safeguard Policy Filter process—and to assign it an initial disaster and climate change risk classification.

The Disaster Risk Management Policy requires project teams to identify whether their projects are "highly exposed to natural hazards or have a high potential to exacerbate risk," which is part of the social and environmental project screening and classification process. ESG developed the Toolkit to assist IDB staff in screening for environmental and social impacts in relation to safeguard policies, including for disaster and climate change risks.

The Toolkit is designed primarily to determine exposure to natural hazards. This is why this step provides only a preliminary classification of disaster and climate change risk. To correct and finalize this classification and thus obtain an integrated risk classification, Step 2 (which looks at project criticality and vulnerability) must be used as a complement of Step 1.

This first step in the Methodology uses a top-down approach. That is, coarse-scale data and maps are used to take a first and quick glance at the contextual conditions of the larger vicinity of the operation. This approach is deemed appropriate for this step, as it is intended to flag big concerns early in the risk assessment process. It is the starting point of a detailed evaluation of these risks for each operation.

4.1.2. Screening and classification process

4.1.2.1. Screening and Classification Toolkit

The Screening and Classification Toolkit developed by ESG is hosted at the IDB's central operations management system (Convergence). Project teams and specialists from the ESG unit can use it to screen their projects for impacts and generate a Safeguard Policy Filter Report and a Safeguard Screening Form, both of which are part of the Project Profile package. The Safeguard Policy Filter Report identifies the Bank policies that have been triggered by the project. The Safeguard Screening Form identifies the potential environmental and social impacts as well as the disaster and climate change risks and, based on their significance, reports the environmental and social category, as well as a preliminary disaster risk classification, assigned to the project.

The Toolkit consists of a questionnaire. The disaster and climate change risk section is divided into the following three subsections:

i. A set of questions regarding the operation's exposure to natural hazards and its vulnerability, its potential to exacerbate existing risks, and the inclusion of activities related to climate change adaptation. These questions are aimed at determining whether the Disaster Risk Management Policy is triggered and if a special focus on climate change is needed.

ii. A set of questions on the specific hazards to which the operation is exposed.

iii. A set of questions on the estimated levels of impacts from the selected hazards to the operation and the possibility that the operation might exacerbate them.

The second and third sets of questions are aimed at providing an initial disaster and climate change risk classification as low, moderate, or high.

To help specialists answer these questions, a GIS-based mapping platform containing numerous natural hazards was developed. Although the mapping platform is a useful and user-friendly resource, the Toolkit enables specialists to use their best professional judgement along with other lines of evidence to determine the magnitude of potential impacts to projects.

4.1.2.2. Mapping platform

This platform allows project specialists to visualize different natural hazard and climate change-related layers for their project location(s) and to identify areas that may be exposed to high or moderate hazard levels. The GIS layers were developed using global data and models with a fairly coarse resolution. Therefore, they should be considered an initial screening aid to better understand those locations that may be more exposed to hazards, and not as exclusively indicative of project-specific risk.

The map application includes 21 layers covering geophysical and hydrometeorological hazards. Ten layers are stationary hazard maps, that is, hazards evaluated without incorporating climate change, and the other 11 are hazard maps considering non-stationarity in hazards, that is, incorporating climate change. Box 4.1 shows what the mapping platform looks like. For more details on the specifics for each hazard layer (i.e., what is depicted for each hazard, what methods and sources are used, and how to read and interpret the climate change layers), see Appendix C.

Specifically, the 10 stationary layers cover the following:

- Seismic hazard
- Volcanic hazard
- Landslide hazard
- Hurricane-wind hazard
- Hurricane-storm surge hazard
- Tsunami hazard
- Drought hazard
- Heatwave hazard
- Riverine flooding hazard
- Wildfire hazard

The 11 non-stationary layers cover the following:

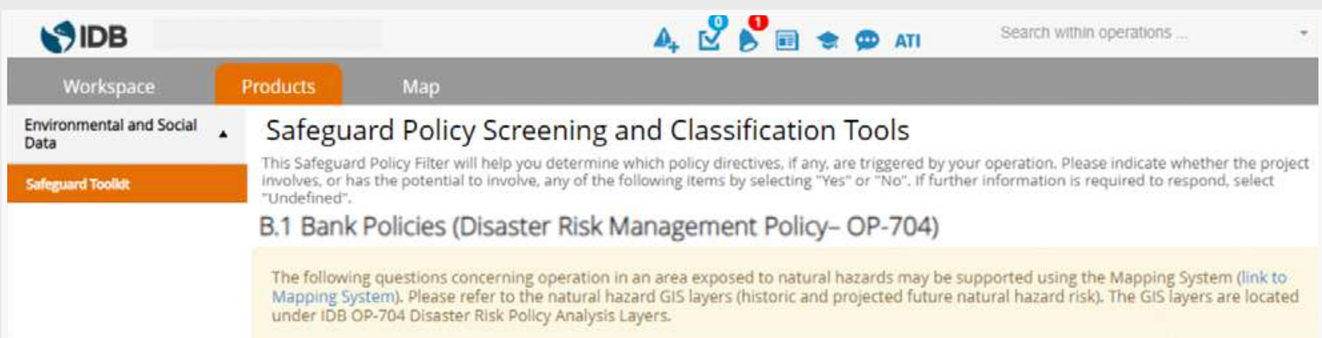
- Drought hazard
- Heatwave hazard under RCP 4.5 and 8.5
- Riverine flooding hazard
- Sea-level rise hazard
- Water scarcity hazard
- Precipitation changes under five different GCMs

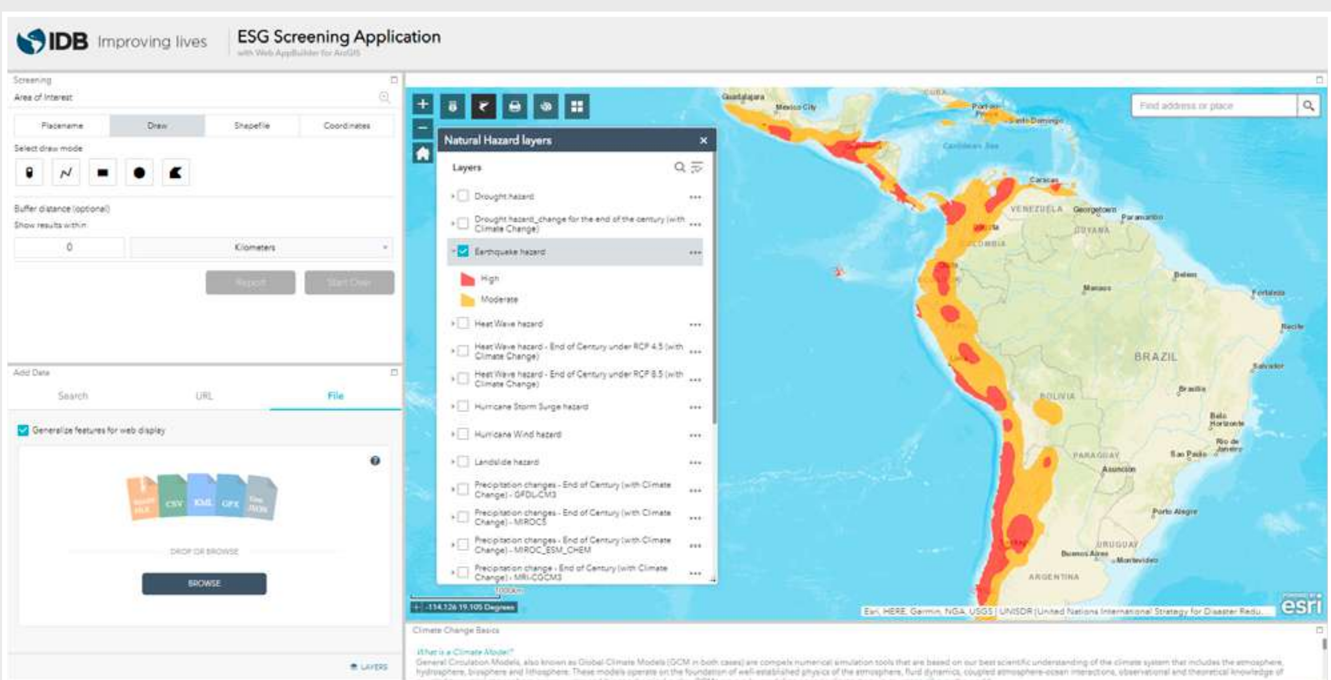
All of the layers, including climate change, depict the projected conditions for the end of the century (by the year 2100). These climate change layers attempt to identify robust indications of what broad changes future climate might bring on top of already existing hazards. This process is often accomplished by, first, investigating the direction in which a change is to be expected and, second, whether the different projection models agree in sign and magnitude. The strongest and clearest signals of change can be found when the forcing is large and when the system has had sufficient time to respond to the altered boundary conditions. Thus, using the worst-case RCP, that is, RCP 8.5, and the longest timeframe, that is, the last decades of the 21st century, helps optimize the signal (high signal-to-noise ratio). It is important to note that using the worst-case RCP and the longest timeframe applies only to screening, precisely because a screening is not a disaster and climate change risk assessment; it merely aims to provide a first alert in broad terms. Thus, this does not necessarily apply to project-specific evaluations, where selection depends on the type of infrastructure under consideration, its design lifespan, sector-specific standards, risk tolerance and risk aversion of project stakeholders, and other project-specific decisions. Steps 3, 4, and 5 provide further guidance on this, depending on the type of risk assessment to conduct and the different types of analyses available.

Box 4.2 presents some key climate change considerations to keep in mind when using climate model projections in general, but specifically when selecting the most appropriate climate variables, scenarios, and models for screening purposes to get a robust signal.

Box 4.1. Support Tool: Hazard maps

The layers cover a range of sources and levels of resolutions responding to the different nature of each hazard and the methods used to model them. For hazards that have been quantified using starndar probabilistic modeling methods, such as seismic, tsunami, stationary hurricane wind, storm surge, and flooding hazards, the output probabilistic hazard layers from the latest Global Assessment Report 2015 (GAR15) were directly Used (UNISDR, 2015). For hazards that do not have a probabilistic representation but that have been quantifies by the GAR using indices, such as volcanic, landslide, and wildfire hazards, the output hazard index layers from the GAR 2009 (UNISDR, 2009) were used. For other more complex hazards, such as drought and heatwave hazards, specific modeling approaches proposed by various scientific papers were used. Finally stationary layers and incorporate climate change to obtain non-stationary hazard layers. See Appendix C for more details and on how to interpret the climate change layers.





Box 4.2. Tips on Using Climate Change Projections for Screening Purposes

For screening purposes, high-level data are sufficient; because the objective is to identify the signal of climate change, there should not be a strong focus on specific values of climate change projections. Only general trends should be used. With this in mind, the direction of change in temperature (warming) is generally highly clear, and even spatial differences are fairly small. For precipitation, however, the model-to-model differences are expected to be higher, and the response fields at the grid point level are commonly much noisier. It is therefore important to assess large-scale patterns of change and see if the change fields show broad, dynamically related structures, or if projections are dominated by grid-point noise and natural variability.

After analyzing means, it is also interesting to look at the tails of the distribution (more extreme conditions) of daily or monthly climate characteristics (e.g., highest precipitation intensities). Additionally, when consulting model projections, it is helpful to consider large ensembles of model outcomes, as individual models might display various forms of bias. A multi-model ensemble of 10 or more models tends to be quite robust.

Finally, as for the time horizon and RCP, a worst-case approach can be taken (for the end of the century and RCP 8.5) just to permit the elucidation of the trends and signals of change.

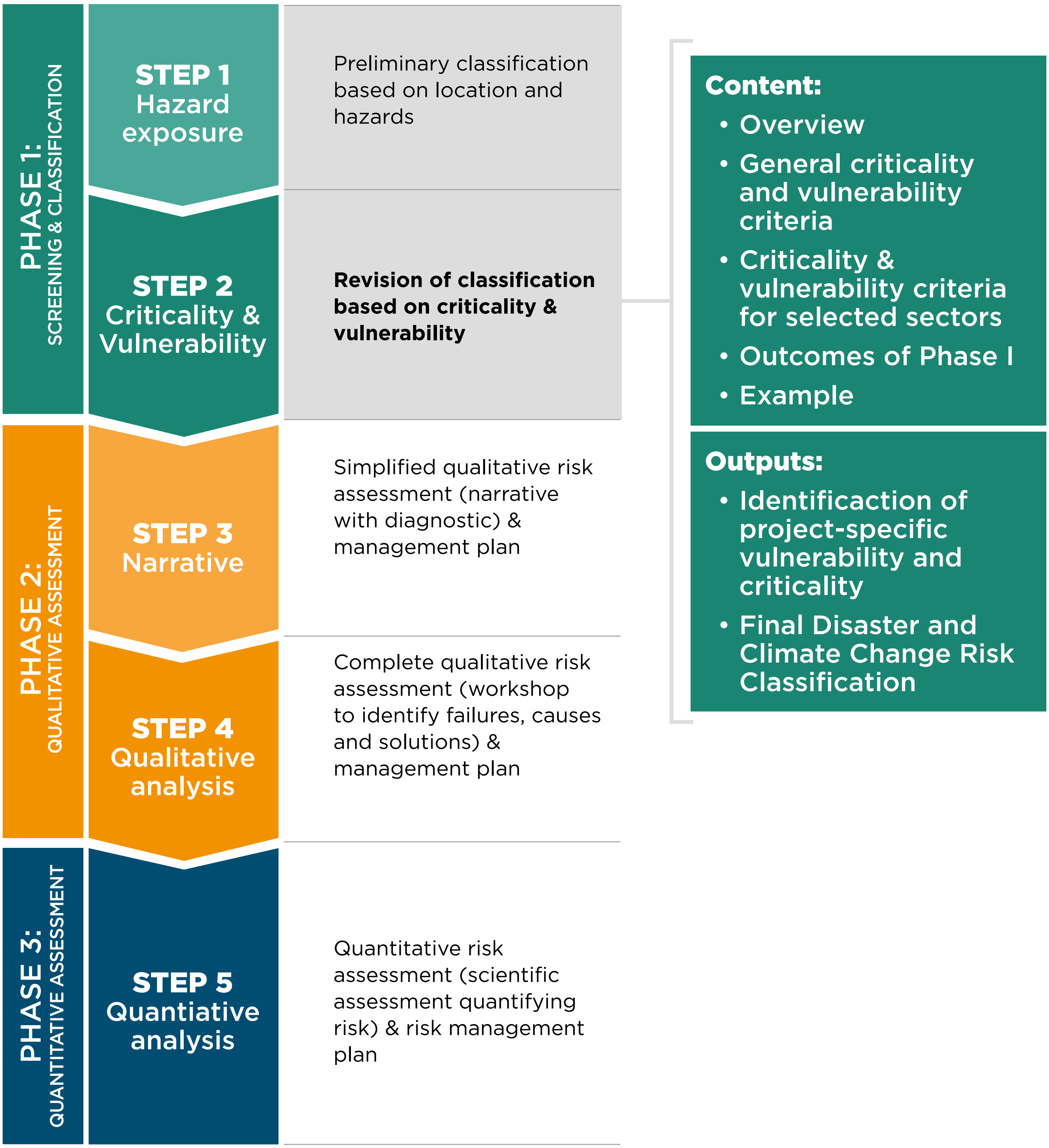
Note that these considerations do not necessarily apply to a disaster and climate risk assessment; details on the special considerations for a project-level risk assessment are presented in Step 5.

4.1.3 Outcomes

Based on the information provided to answer the questions, the Toolkit assigns an initial and preliminary disaster and climate change risk classification of low, moderate, or high (in addition to an Environmental Category of A, B, or C). Then, through the Safeguard Screening Form, the Toolkit provides general guidance based on the language in the Disaster Risk Management Policy on the next steps that are appropriate for the applicable rating. However, all projects must necessarily advance to Step 2 of the Methodology, where this initial classification will be further analyzed and complemented with a perspective on the criticality and vulnerability of each individual project.

4.2. Step 2: Revision of Classification Based on Criticality and Vulnerability

Figure 4.2 . Step 2



4.2.1 Overview

The second step, centered on the project's criticality and vulnerability, complements the result from the previous step to obtain a disaster and climate change risk classification for the operation itself and not merely the hazards. The objective of this step is to better understand the project's characteristics and determine its vulnerability to natural hazards and the criticality of interrupting or cancelling the services or, more broadly, the benefits provided by the project in response to damages that might result from these hazards. This step is designed as a bottom-up approach, as the focus shifts to a project-level examination of the estimated response and vulnerability of the infrastructure.

Understanding the project's specific characteristics, including size, physical structure, functionality, lifespan, and typology, and its response to the natural hazards previously identified in Step 1, adds a second layer of reasoning to inform the disaster and climate change risk classification. This will help identify critical project attributes and clarify how the hazards of interest may impact the project as well as the surrounding community, the environment, and its sustainability. The importance of complementing hazard and climate change information with project vulnerability and criticality data became apparent after analyzing disaster and climate change risk assessments or equivalent studies conducted for projects from 2014 to 2017.

Box 4.3. Criticality and Vulnerability

Criticality refers to the degree of significance that a structure or system holds within a larger context due to the type and scale of services or functionality it provides. **Vulnerability** refers to the inherent qualities that determine a structure's (or system's) susceptibility to suffer damage. It encapsulates the proneness of a project in the face of a hazard. Both concepts lead to a better understanding of the potential consequences (physical impacts on the structure and on population and services) that a failure of the operation due to natural hazards would create. Both must be defined in consultation with the relevant sector specialists.

The main output from Phase 1 is a classification of the disaster and climate change risk for the project. This classification has three possible values: low, moderate, and high. To establish a classification, aspects of the exposure of the project to natural hazards, the intensity of these hazards (Step 1), and the project's criticality and vulnerability (Step 2) should be considered and weighed using professional best judgement to arrive at a comprehensive appraisal of the risk conditions. If as a result of Step 2 there is a new classification, the safeguards screening form needs to be updated accordingly. If an operation is categorized as low risk, it may exit the process at this point; all others must advance to Phase 2.

The following sections will provide examples of how to facilitate the process of recognizing what features make a structure or system more or less critical and vulnerable, including general questions on physical characteristics, level of service provided, and magnitude of potential negative effects on third parties. Three subsector-specific charts developed in cooperation with sector specialists will illustrate this concept for roads, water and sanitation infrastructure, and hydroelectric dams. These charts reflect both the most universal and the technically pertinent attributes for each type of infrastructure that are the source of the sector's main concerns.

4.2.2 General criticality and vulnerability criteria

This section contains the general questions that may be asked to establish the criticality and vulnerability of any project with an infrastructure component—either a stand-alone infrastructure project (e.g., a hydroelectric dam) or an operation with infrastructure components (e.g., a school program that is financing, among other things, school buildings). The answers to these questions will enable a better understanding of the key characteristics and scope of the project, which in turn will help assess potential impacts.

Often, at the beginning of the project preparation process, few details are known. Step 2 asks questions about the project scope, such as physical characteristics (e.g., if it is a road, will it include bridges), potential interaction with population and environment (e.g., for a dam, is there a population center close by that could be affected if the dam fails), potential impacts in case of loss of service (e.g., if the water project fails, how many people could be left without water). This step guides the team to think about issues such as the population that would be served by the project, the project value, the subsector(s) in which the project is embedded, the kinds of buildings and infrastructure that would be built or modified and the quantities of each, and the anthropic and natural environment in the project's influence area. This can be done either through a table or chart or by asking a set of questions.

Box 4.4. Multi-sectoral and Multiple Works Operations

For **multi-sectorial and/or multiple works operations**, where more than one subsector is represented and/or works are physically independent of one another, although each individual project should be evaluated, the criticality and vulnerability of the operation as a whole should be assessed. Following the same criterion applied to environmental and social aspects, the highest classification assigned to an individual project in the sample should be the guiding classification.

Notes: Multiple-works loans are more open-ended than loans for specific projects. They are designed to finance groups of similar works that are physically independent of one another and whose feasibility does not depend on the execution of any given number of the works projects. Because not all subprojects to be financed by the loan are known by the time the IDB approves the loan, borrowers should specify a representative sample of subprojects before the loan is approved. This sample should constitute approximately 30 percent of the project's cost. While the project is being executed, individual investments are financed in accordance with the eligibility criteria specified in the loan proposal. Examples of eligible activities include financing water and sanitation services in numerous rural areas with not all of them being identified before the IDB approves the project. See IDB Investment Lending Category: https://www.iadb.org/en/about-us/idb-financing/investment-loans%2C6056.html.

First, some notes on project scope, infrastructure lifespan, and potential project failure:

(a) The **project scope** will likely provide some guidance on the elements that may require further analysis, and the information that might already be available. For example, the team may ask:

- If there are no existing structures, will the operation define every design and operation parameter from the early concept stages? (e.g., design/build projects).
- Are there any existing structures that are already in the construction or operation stages? Will upgrades be made only to specific parts?[12] (For example, not to the complete infrastructure—modernization/upgrade projects.)
- Is it a planning project involving infrastructure?

(b) With respect to the project's vulnerability, a key question to ask is what the **infrastructure's lifespan** is. This might inform the decision on whether to conduct a more thorough risk assessment. Table 4.1 shows examples of typical lifespans used by different industries. As standards vary depending on the country context, they should only be considered indicative, and the project-specific values should be used in each operation.

12 Note that in certain cases, modernization/upgrade projects may require a study of the entire structure, rather than only of the sections being upgraded.

Table 4.1. Typical Infrastructure Lifespans

Project type	Project component	Typical lifespan
Water utility	Water treatment plant	30 Years
Water utility	Pump station	30 Years
Water utility	Storage tank	50 Years
Water utility	Well	30 Years
Water utility	Distribution network	50 Years
Water utility	Instrumentation and controls	10 Years
Water utility	Service connections	30 Years
Wastewater/sewer utility	Wastewater treatment plant	30 Years
Wastewater/sewer utility	Lift station	30 Years
Wastewater/sewer utility	Septic field	25-30 Years
Wastewater/sewer utility	Sewer network	35 Years
Wastewater/sewer utility	Instrumentation and controls	10 Years
Transportation	Asphalt road	50 Years
Transportation	Gravel road	50 Years
Transportation	Bridge	75 Years
Transportation	Tunnel	75 Years
Social facilities	Hospital/healthcare center	30-50 Years
Social facilities	School	30-50 Years
Drainage	Stormwater network	50 Years
Drainage	Wet ponds	20 Years
Drainage	Dry extended detention basins	20 Years
Drainage	Constructed stormwater wetlands	20 Years
Drainage	Bioretention areas	20 Years
Drainage	Permeable pavement	20 Years
Drainage	Cisterns and rain barrels	20 Years
Drainage	Green roofs or vegetated roofs	20 Years
Drainage	Tree box filter	20 Years
Drainage	Sand filter	20 Years
Drainage	Grassed swales	20 Years
Energy/water	Hydroelectric dams	50 years
Energy/water	Safety components (e.g., gates and valves)	20–25 years
Water regulation and distribution	Reservoirs, channels, and transfers	25–50 years

Source: TetraTech and IDB professional judgment.
Note: (i) Lifespan refers to the lifespan of the infrastructure itself and not that of the IDB's operation. (ii) Schools may serve as emergency response shelters. (iii) The safety components associated with a dam have a direct relation to flood risk management. They have a 20–25-year lifespan if properly maintained (Martins Nogueira and Alarcon, 2019).

(c) The most important factor to think about in this step is: What are the potential consequences of project failure, including to surrounding communities and the environment? For example:

a. If the project fails, is there a potential for loss of life?
b. How many people will this project support? If it were to fail, how many people would lose a critical service?
c. Is there redundant infrastructure which can be used if this project fails?
d. Would there be significant loss of ecosystems services?
e. Could the construction or existence of the project exacerbate the risk of any of the hazards for surrounding communities?

The point of Step 2 is to have this conversation with the specialists in the relevant project typology beforehand, to be able to determine the key characteristics of a project typology that, in general, make it more critical. This facilitates the high-, moderate-, or low-risk screening. The reasoning behind this step is that, although there can be uncertainty about the hazard, there is more certainty on what makes a project critical. Box 4.5 shows first an example of the sort of questions that can help guide a team when a criticality and vulnerability table has not yet been developed.

Box 4.2. Tips on Using Climate Change Projections for Screening Purposes

For subsectors or project typologies for which a criticality and vulnerability table has not yet been developed with the sector specialists, the following characteristics are useful for thinking about criticality and vulnerability. In using this matrix, apply a conservative approach. That is, the highest category found for each individual characteristic should apply to the entire operation. The thresholds should be determined with expert opinion from the sector and should be used as general guidance. They can be revised or replaced with others that may be more appropriate for specific contexts. See Boxes 4.6, 4.7, and 4.8 for examples of criticality and vulnerability tables where these questions have been developed with sector specialists.

Key Characteristics	Low	Moderate	High
Key physical characteristics that make a project more vulnerable (for example, for roads, are there bridges?)	Example: no bridges	Example: at most x critical bridge(s)	Example: x or more critical bridges
Potential loss of life associated with project failure (could be more precise, for example some sectors have standards for this)	Unlikely	Likely	Very likely
Number of people supported,[a] for whom service might be interrupted	<x [b]	x to y	>y
Redundant infrastructure?	Yes	Partial – to be defined case by case	No
Project value (US$)	<x	x to y	>y
Potential significant loss of ecosystem services	Unlikely	Likely	Very likely
...and any other relevant characteristics according to the project typology or area of intervention	...	...	...

[a] That is, peole that benefit from the service provided by the infrastructure.
[b] Values are not given because this should be determined through a workshop (or similar exercise) with the specialists in the project typology and they can be context specific.

The information from Step 2 will need to be weighed together with the hazard screening in Step 1 to obtain an overall estimated risk classification for the project. Additional project-specific questions regarding structural and operational characteristics should complement these to determine if additional studies are needed. This is the goal of Step 3.

4.2.3 Criticality and vulnerability criteria for selected sectors

This section presents examples of subsector-specific charts to illustrate the concept of criticality and vulnerability for roads, water and sanitation systems, and hydroelectric dams. It first looks at each subsector in more detail, and then at the respective criticality and vulnerability table. A section on social facilities has been added, for which a criticality table is still under development. The subsector discussion is included to help the user think about the characteristics of each project type that are affected, and to what extent, by different natural hazards.

4.2.3.1 Water and sanitation, and drainage

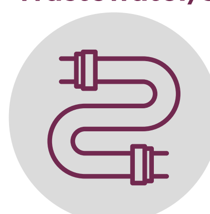
4.2.3.1.1 Brief description

Drainage. Drainage infrastructure routes stormwater runoff away from buildings, roads, and other critical infrastructure as quickly and efficiently as possible. While effective at protecting infrastructure near the source of the excess runoff, this potentially leads to increases in downstream flooding and structural damage. In response to this, flood control approaches incorporating temporary runoff storage upstream of areas of flooding concern have been adopted. Stormwater treatment evolved beyond "gray" infrastructure (curbs, gutters, culverts) to include stormwater wet ponds and wetlands, and later on various green infrastructure[13] practices (see Appendix I).

Water utility. Water utility infrastructure generally includes a supply source (surface, spring,

or groundwater), treatment, pumping, storage, and distribution systems (to convey the treated water to the end-user customers), instrumentation and controls (to report the condition of the water utility infrastructure to operational staff), and service connections (system that joins the local water line to the end-user customer).

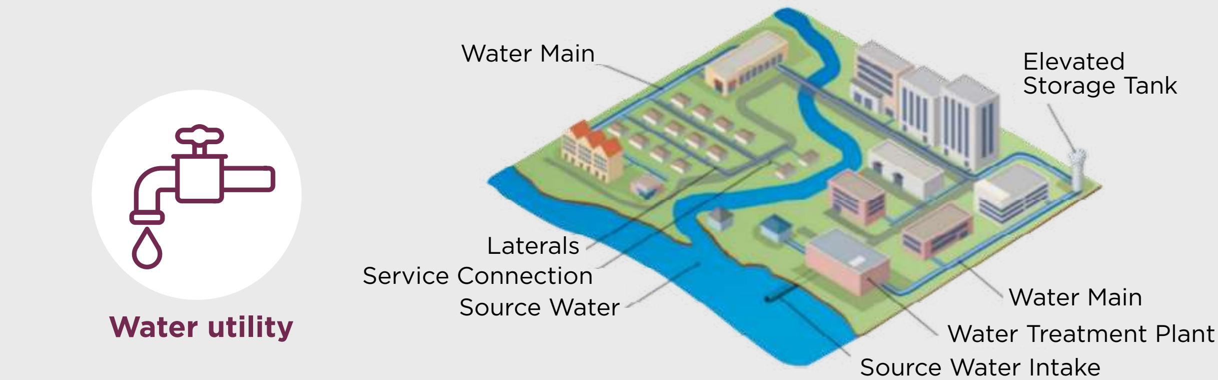
Wastewater/sewer utility. Typical wastewater



utility projects include three main components: collection/conveyance, treatment, and product disposition. The collection/conveyance infrastructure consists of the pipes that move wastewater from where it is generated to where it will be treated. Treatment describes any process intended to change the wastewater in a way that makes it easier to treat or more appropriate to disperse into the environment. Product disposition typically refers to the final management of the treated wastewater effluent, which is often dispersed into the environment (i.e., discharged to surface waters, distributed within the soil) or reused.

13 Green Infrastructure is a "cost-effective, resilient approach to managing wet weather impacts that provides many community benefits. While single-purpose gray stormwater infrastructure—conventional piped drainage and water treatment systems—is designed to move urban stormwater away from the built environment, green infrastructure reduces and treats stormwater at its source while delivering environmental, social, and economic benefits." See: What is Green Infrastructure? EPA: https://www.epa.gov/green-infrastructure/what-green-infrastructure.

Box 4.6. Drainage and Water and Sanitation Infrastructure



4.2.3.1.2 Criticality and vulnerability chart

After holding a working session with sector specialists from the Water Sector, the following key characteristics were deemed important to determine criticality and vulnerability of drainage, water, and wastewater infrastructure:

4.2.3.1.3 Loss of essential services

i. If there were an interruption of the service due to the infrastructure failure, how many people could be affected?

4.2.3.1.4 Impact to population

i. If the retaining structures were to fail, is it likely that there would be physical damages? Is it likely that there would be people affected? If so, could there potentially be loss of life? Could there be environmental damages?

4.2.3.1.5 Physical characteristics

i. Are there retaining structures? If so, how high are they?

ii. What is the volume retained?

The result from this thinking process is a system that rates criticality and vulnerability as either low, moderate, or high using the three dimensions mentioned above (i.e., loss of essential services, impacts on population, and physical characteristics). The highest category obtained in any of the three is taken as the overall classification (conservative approach).

Dimension 1: Loss of essential services

In these types of infrastructure projects, criticality is linked to the loss of the ability to provide the essential services of drainage, potable water supply, and wastewater management due to a failure of the system. Hence, an indicator of the magnitude of the loss of provision of essential services has been selected to represent this dimension. Table 4.2 shows the quantitative thresholds defined for it. These are indicative; the thresholds may need to be revised depending on the context.

Table 4.2. Indicative Thresholds for Dimension 1

Component	Low	Moderate	High
Impacts on service functionality	Failure in the provision of drainage services, potable water supply, and wastewater management affects a municipality with fewer than 10,000 inhabitants	Failure in the provision of drainage services, potable water supply, and wastewater management affects a municipality with a population between 10,000 100,000 inhabitants	Failure in the provision of drainage services, potable water supply, and wastewater management affects a municipality with more than 100,000 inhabitants

Dimension 2: Impacts on population

In these types of projects, impacts on the population are related to the number of inhabitants that may potentially suffer damages (including loss of life) due mainly to the failure or collapse of any of the water-retaining structures, such as dykes, reservoirs, and dams, among others. Hence, an indicator of the magnitude of damages and loss of life has been selected to represent this dimension. Table 4.3 shows the qualitative thresholds defined for it.

Table 4.3. Indicative Thresholds for Dimension 2

Component	Low	Moderate	High
Impacts on population	The failure of water-retaining structures causes moderate physical damages to other assets and no loss of life	The failure of water-retaining structures causes important physical damages to other assets and/or the environment, or affects a small number of households	The failure of water-retaining structures gravely affects urban centers or essential services and causes significant physical damage to other assets and/or the environment

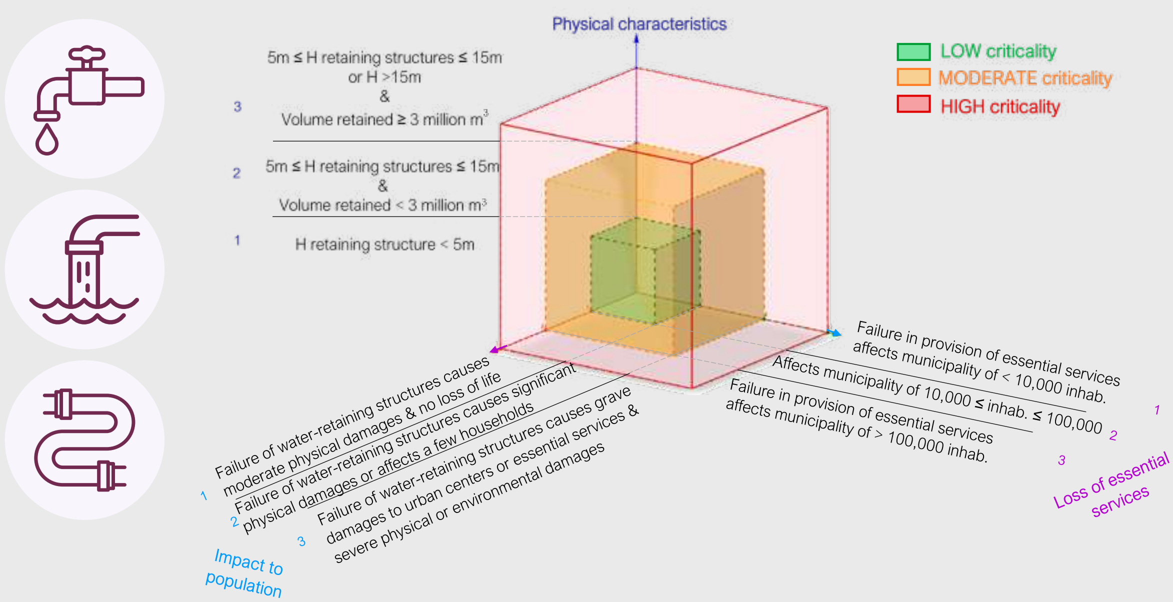
Dimension 3: Physical characteristics

In these types of projects, various kinds of components merit special consideration due to their ability to release large quantities of water in an uncontrolled manner in the event of a failure. These structures are the same ones as those mentioned in Dimension 2: dykes, reservoirs, and dams, among others. Hence, the existence and characteristics of these structures have been selected to represent this dimension of vulnerability. Table 4.4 shows the quantitative thresholds defined for it.

Table 4.4. Indicative Thresholds for Dimension 3

Component	Low	Moderate	High
Physical characteristics of water-retaining structures	Existence of water-retaining structures with a height of less than 5 meters	Existence of water-retaining structures with a height between 5 and 15 meters and a storage capacity of less than 3 million cubic meters	Existence of water-retaining structures with a height between 5 and 15 meters or above 15 meters and a storage capacity of more than 3 million cubic meters

Box 4.7. Criticality and Vulnerability Table for Drainage and Water and Wastewater Infrastructure



Support questions that guided the criticality and vulnerability discussion: drainage, water, and sanitation infrastructure

Below is a list of the aspects that were considered relevant to the discussion for assessing the criticality and vulnerability of drainage, water, and sanitation infrastructure and that helped to arrive at the criticality and vulnerability table. Discussions on these aspects with sector experts led to the creation of a table that integrates all (or most) of these parameters and enables criticality and vulnerability levels to be categorized.

- **Scale** of the project (number of people served, etc.). [This is captured in the criticality table.]
- **Type of structure** (water retaining structures, water storage, networks of pipes, channels, treatment plants, etc.). [This is captured in the criticality table.]
- **Construction methods** used (e.g., underground systems, etc.).
- Design **return periods** for the operation of hydraulic elements, if applicable (i.e., for rain management).
- Existence of **hydrogeology-related problems** (i.e., susceptibility to flooding, earthquakes, and other natural hazards).
- Existence of **singular structures** (i.e., water-retaining structures such as dams or reservoirs), the implications in case of failure, and importance. [This is captured in the criticality table.]
- **Potential to affect population** due to failure of water retaining structures. [This is captured in the criticality table.]

To create the criticality and vulnerability table, the following guiding dimensions were considered:

<u>Scope of the subsector</u>: Although this subsector includes three distinct services—water supply, wastewater treatment, and flood control—they share many characteristics in terms of the types of structures they include and their susceptibility to natural hazards. Thus, disaggregating these services was found to be unnecessary, and an overall approach can be adopted as long as these specifics are considered.

<u>Relevant structures involved</u>: Among the different types of structures involved in these systems, those with the ability to retain large volumes of water are considered to be the most concerning, as they pose a significant threat given their potentially disastrous consequences if they were to fail (including collapse).

<u>Natural hazards</u>: The most important natural hazards are flooding at a systemic level, and earthquakes and landslides at more localized levels for specific structures.

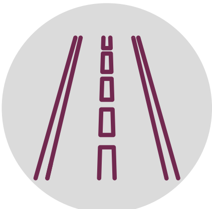
<u>Need to disaggregate key parameters into various tables</u>: It is not considered necessary to create more than one table, but it is important to distinguish between infrastructure designed specifically for flooding risk reduction from that which serves other purposes such as transportation, energy, water, energy projects, or others.

<u>Key dimensions required</u>: Three main dimensions were identified as encompassing all the above-mentioned features: **loss of essential services, impacts on population, and physical characteristics**.

The result from this thinking process led to the information contained in Tables 4.2, 4.3, and 4.4 and Box 4.7.

4.2.3.2 Roadway infrastructure

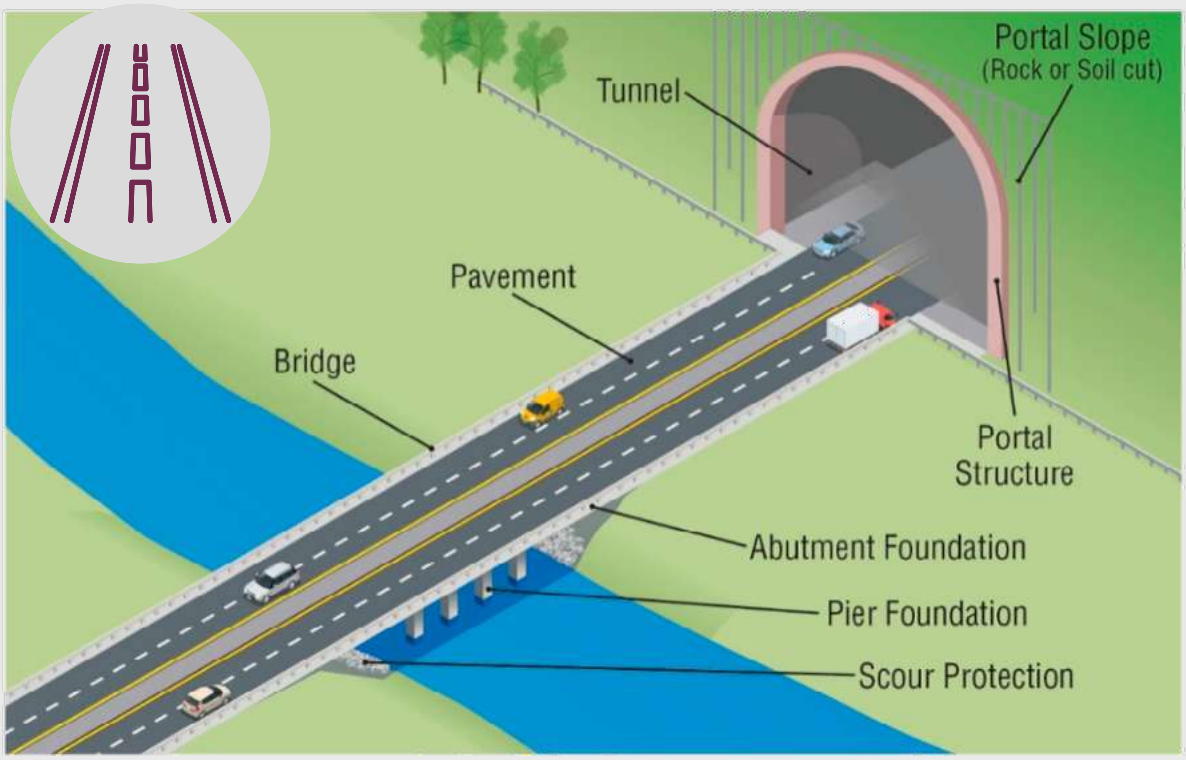
4.2.3.2.1 Brief description



Roadway infrastructure includes roadways, bridges, tunnels, and the following components: cut slopes, fill slopes, embankments, ditches, culverts, drainage structures, retaining walls, over- and underpasses, and pavement (see Box 4.8).

Roadway infrastructure is particularly vulnerable to earthquakes, floods, and landslides, and in some cases, volcanic eruptions and snowstorms as well (Bengtsson, 2008). While other hazards with slower onset such as heatwaves may influence the durability and maintenance of the pavement structure in the long term, their impact is less significant. Furthermore, different scenarios may trigger a specific failure mode depending on a project's particular circumstances. For instance, a road may be very vulnerable to earthquakes if located on soil that favors liquefaction, while it may be negligibly vulnerable to flooding because it has drainage and protection structures.

Box 4.8. Roadway Infrastructure



4.2.3.2.2 Criticality and vulnerability chart

After holding a working session with sector specialists from the Transport Sector, the following key characteristics were deemed important to determine criticality and vulnerability of roadway infrastructure:

4.2.3.2.3 Loss of essential services

i. Would essential services be easily accessible after failure?

4.2.3.2.4 Interaction with the natural and anthropic environment

i. Are there sections with elevated slopes? Could landslides cause major damage? Could major population settlements be directly affected? Does the road generate new settlements?

4.2.3.2.5 Physical characteristics

i. Does the road include bridges, tunnels, or numerous drainage structures of great capacity?

The result from this thinking process is a system that rates criticality and vulnerability either low, moderate, or high using three main dimensions where the highest category obtained in any of the three is taken as the overall classification (conservative approach).

Dimension 1: Loss of essential services

In road infrastructure projects, the loss of essential services due to a failure of the system can be linked to the connectivity and the transit capacity that the infrastructure ceases to provide once failure occurs. Hence, these two indicators of functionality (accessibility and hourly traffic) were selected to represent this dimension. Table 4.5 shows the qualitative and quantitative thresholds defined for each indicator. To obtain a unique categorization of criticality and vulnerability for this dimension, the worst (lowest) classification of either criteria should be used.

Table 4.5. Indicative Thresholds for Dimension 1

Component	Low	Moderate	High
Accessibility level after failure	Essential services are easily accessible after failure	Essential services are moderately accessible after failure	Essential services are inaccessible after failure
Hourly traffic	0–600 vehicles per hour	600–1200 vehicles per hour	More than 1200 vehicles per hour

Dimension 2: Interaction with the natural and anthropic

Road infrastructure projects have the main characteristic of being linear structures that span great lengths (usually at least tens of kilometers) that may increase the exposure of the road to different hazards, increasing the risk and the potential consequences of failure. Hence, two indicators of this exposure (presence of slopes and urban centers) have been selected to represent this dimension. Table 4.6 shows the qualitative thresholds defined for each of these indicators. To obtain a unique categorization of criticality and vulnerability for this dimension, the worst (lowest) classification of either of the criteria should be used.

Table 4.6. Indicative Thresholds for Dimension 2

Component	Low	Moderate	High
Slopes	The road alignment goes through few or no sections with elevated slopes, and landslides would not cause damage to the road.	The road alignment goes through some sections with elevated slopes, and landslides may cause partial destruction of the road.	Most of the road alignment goes through sections with elevated slopes, and landslides may cause destruction of most of the road.
Urban centers	The road has incidence on a population center that has low importance for the area's economic activity; the road thus generates few (or no) settlements surrounding the road and connects urban centers of low importance.	The road has incidence on a population center that has moderate importance for the area's economic activity; the road thus generates settlements surrounding the road and connects urban centers of moderate importance.	The road has incidence on a population center that has major importance for the area's economic activity; the road thus generates multiple settlements surrounding the road and connects large urban centers.

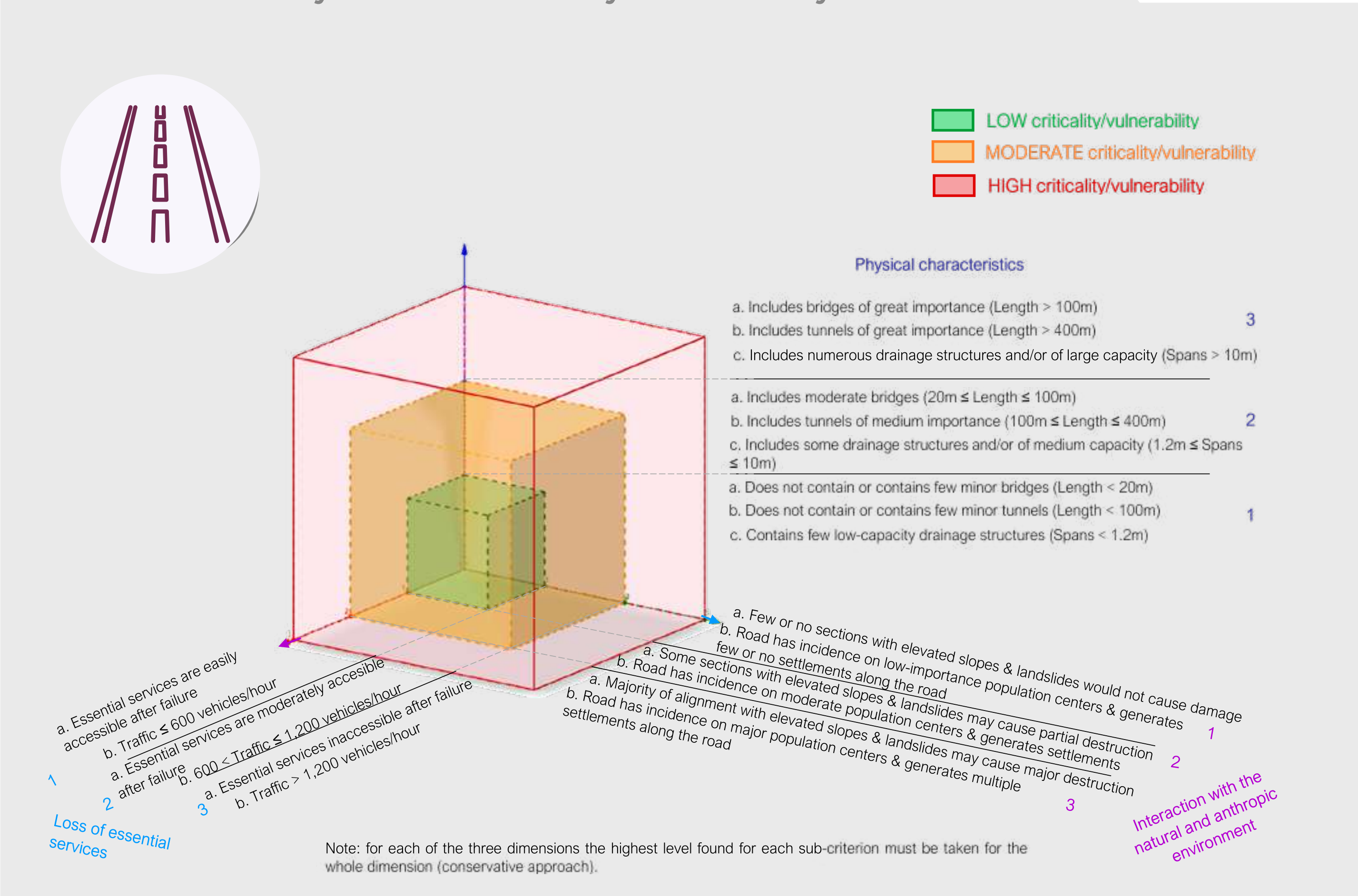
Dimension 3: Physical characteristics

In road infrastructure projects, the physical and/or structural characteristics refer to singular works that may exist throughout the road alignment. Singular works or structures are bridges, tunnels, and drainage works, where the latter is related to the road's potential capacity to act as a barrier and flood large areas (Box 4.9). Hence, three indicators of this (presence of bridges, tunnels, and transversal drainage works) haven been selected to represent this dimension. Table 4.7 shows the qualitative and quantitative thresholds defined for each indicator. To obtain a unique categorization of criticality and vulnerability for this dimension, the worst (lowest) classification of either of the criteria should be used.

Table 4.7. Indicative Thresholds for Dimension 3

Component	Low	Moderate	High
Presence of bridges	The road alignment does not contain or contains few minor bridges (Length < 20m).	The road alignment contains moderate bridges (20m < Length < 100m).	The road alignment contains major bridges (Length > 100m).
Presence of tunnels	The road alignment does not contain or contains few minor tunnels (Length < 100m).	The road alignment contains tunnels of medium importance (100m < Length < 400m).	The road alignment contains tunnels of great importance (Length > 400m).
Presence of transversal drainage works	The road alignment contains few low-capacity transversal drainage structures (Spans < 1.2m).	The road alignment contains some transversal drainage structures and/or of medium capacity (1.2m < Spans < 10m).	The road alignment contains numerous transversal drainage structures and/or of large capacity (Spans > 10m).

Box 4.10. Criticality and Vulnerability Table for Hydroelectric Dams



Note: for each of the three dimensions the highest level found for each sub-criterion must be taken for the whole dimension (conservative approach).

4.2.3.2.6 Questions that guided the criticality and vulnerability discussion: roadway infrastructure

Typically, the importance or criticality of a roadway is viewed in terms of its performance-level requirement. High-importance roadways are considered to have a corresponding high performance-level requirement (typical descriptions for high-performance roads include lifeline roadways, considered critical for disaster response; roadways of significant economic importance because they connect a resource or goods from source to markets; roadways with significant traffic volumes; and roadways of strategic importance). Moderate- and low-importance roadways are more local and regular-use roads.

To analyze the vulnerability of a linear structure as a road, usual approaches include using (i) travel costs and/or (ii) Hansen's accessibility index (Bengtsson, 2008). Due to the variety of ways in which a road-type infrastructure can fail, all the different failure modes can be homogenized using an integrated travel cost that includes both the cost of repairing/reconstructing the road and the cost of the time lost by users. Contrary to what occurs in other types of civil infrastructure, the main consequences from an eventual failure of this type of infrastructure are more related to the inability to use it and the associated effects on the population, and less so to loss of life.

Aspects identified as relevant to the discussion of assessing the criticality and vulnerability of roadway infrastructure, which informed the elaboration of the criticality and vulnerability table, are listed below. Discussions on these aspects with sector experts led to the creation of a table that integrates all (or most) of these parameters and enables criticality and vulnerability to be categorized.

- **Scale** of the road (lifeline, national, regional, local, etc.)
- **Type of traffic** (hazardous merchandise, trucks, tourism, etc.)
- **Traffic demand** and rate of demand/capacity
- Expected **functionality** (i.e. improvements in terms of travel times and/or costs, accessibility to essential services) [Included in the criticality table.]
- **Proximity to major urban hubs** and intersection with other relevant infrastructures [Included in the criticality table.]
- Existence or lack of **redundancy** in the network (i.e., availability of alternative connectivity options)
- Percentage of road sections in **embankments, cuts, and fills**, and magnitude of earth-moving works [Included in the criticality table.]
- Existence of **hydrogeology-**related problems (i.e., crossing of natural water bodies, presence of soft soils, expansive clays, potential of liquefaction, water table levels, presence of potentially dangerous slopes, slope instability conditions) [Indirectly included in the criticality table.]
- Existence, implications, and importance of **singular structures** such as bridges and tunnels, (i.e., constructive procedures, criticality to the functionality of the road) [Included in the criticality table.]

To create this table, the following guiding dimensions were considered:

Scope of the subsector: Although the roadway subsector is complex because of the number and variety of potentially relevant structures it encompasses, an aggregated approach was considered.

Relevant structures involved: Aside from the road itself as the conventional structure, singular structures such as tunnels and bridges have a significant weight in the criticality and vulnerability of the grouped entity.

Relevant natural hazards: The most relevant natural hazards are earthquakes, floods, and landslides.

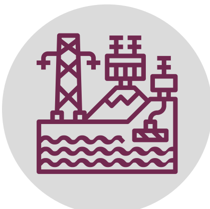
Need to disaggregate key parameters into various tables: It is not considered necessary to create more than one table, but it is key to distinguish between the main hazards that engender a failure of the infrastructure given their distinct implications. For example, earthquakes may have extensive and major impacts, while floods may have more restricted impacts, and landslides may have even more localized effects.

Key dimensions required: Three main dimensions were defined as encompassing all the above-mentioned features: **loss of essential services, interaction with the natural and anthropic environment, and physical characteristics.**

The result from this thinking process led to the information contained in Tables 4.5, 4.6, and 4.7 and Box 4.8.

4.2.3.3 Hydroelectric dams

4.2.3.3.1 Brief description



For hydroelectric projects, which are inherently complex and diverse, a series of aspects need to be considered to evaluate their criticality and vulnerability. These include the storage capacity of the reservoir, the type of dam, the height of the dam, the area affected by a potential failure, the type of spillway, whether spillway water flows through open channels or pressurized pipes, whether there are control and regulation elements in the spillway, whether there is a recharge chamber, and the type of turbine, alternator, and transformer, among others.

4.2.3.3.2 Criticality and vulnerability table

After holding a working session with specialists from the Energy Sector, the following questions were deemed important to determine the criticality and vulnerability of hydroelectric dams:

4.2.3.3.3 Loss of essential services

i. What percentage of the country's electric supply would be provided by the dam?

4.2.3.3.4 Interaction with the natural and anthropic environment

i. If the dam were to fail, would there likely be major physical damages and loss of life? Could major population centers be affected?

4.2.3.3.5 Physical characteristics

i. What is the height of the dam? What is the volume of water stored?

The result from this thinking process is a system that rates criticality and vulnerability either low, moderate, and high, using three main dimensions where the highest category obtained in any of the three is taken as the overall classification (conservative approach).

Dimension 1: Loss of essential services

In hydroelectric projects, the loss of essential services due to a failure of the system can be linked to dependence on the electrical supply provided by the central facility to the region or country where it is located. Hence, this indicator of installed power (in terms of the share of the country's power supply corresponding to the hydroelectric power plant under study) has been selected to represent this dimension. Table 4.8 table shows the quantitative thresholds defined for it.

Table 4.8. Indicative Thresholds for Dimension 1

Component	Low	Moderate	High
Loss of essential services	Hydroelectric power plant with installed power representing less than 1% of the country's electrical supply	Hydroelectric power plant with installed power representing between 1% and 10% of the country's electrical supply	Hydroelectric power plant with installed power representing more than 10% of the country's electrical supply

Dimension 2: Impacts on the population

In hydroelectric projects, the impacts on the population are related to the number of inhabitants downstream of the hydroelectric dam that could potentially suffer damages (including loss of life) due to a failure of the dam retaining water or the uncontrolled opening of the system gates. Hence, this indicator of the magnitude of potential damage has been selected to represent this dimension. Table 4.9 shows the qualitative thresholds defined for it.

Table 4.9. Indicative Thresholds for Dimension 2

Component	Low	Moderate	High
Impacts on population	The failure of the dam causes moderate physical damage to other assets and no loss of life.	The failure of the dam causes significant physical damage to other assets and/ or the environment or affects a few households.	The failure of the dam gravely affects urban centers or essential services and causes very significant physical damage to other assets and/or the environment.

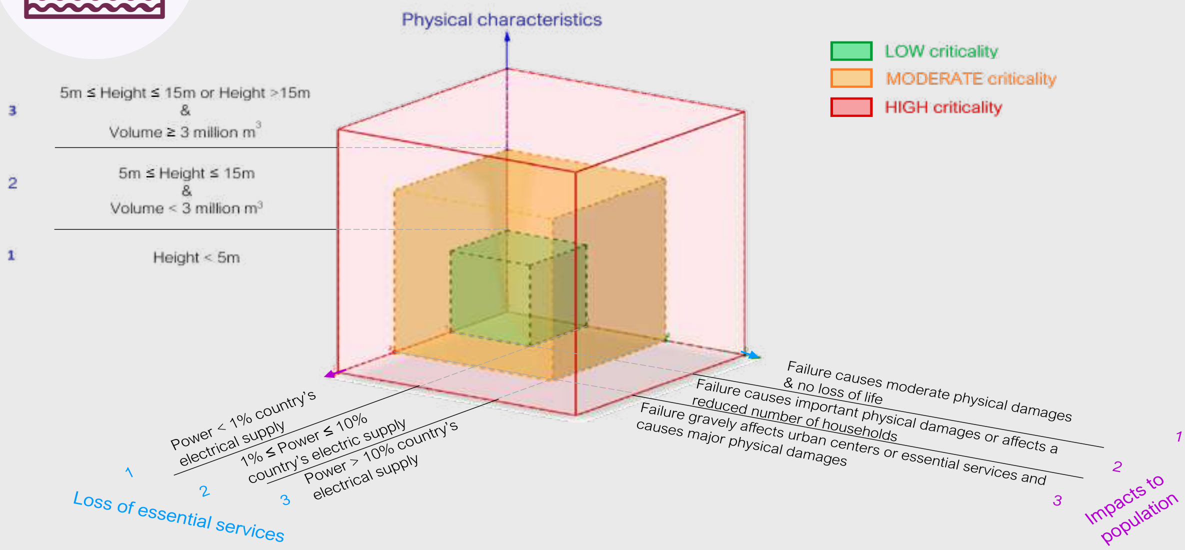
Dimension 3: Physical characteristics

In hydroelectric projects, the physical and/or structural characteristics that are most related to potentially generating disastrous consequences are the height and the storage capacity of the dam. According to ICOLD (2011), large dams are defined as those whose height from the foundation is more than 15 meters, or between 5 and 15 meters with a storage capacity of more than 3 million cubic meters. Hence, an indicator of these two characteristics (dam height and storage capacity) based on this definition has been selected to represent this dimension. Table 4.10 shows the quantitative thresholds defined for it.

Table 4.10. Indicative Thresholds for Dimension 3

Component	Low	Moderate	High
Physical characteristics	Dam height is less than 5 meters.	Dam height is between 5 and 15 meters, and the storage capacity is less than 3 million cubic meters.	Dam height is greater than 15 meters or between 5 and 15 meters, and the storage capacity is greater than 3 million cubic meters.

Box 4.10. Criticality and Vulnerability Table for Hydroelectric Dams



4.2.3.3.6 Questions that guided the criticality and vulnerability discussion: Hydroelectric dams

Aspects that were relevant to the discussion for assessing the criticality and vulnerability of hydroelectric dams and that helped to arrive at the criticality table are listed below. Discussions on these aspects with sector experts led to the creation of a table that integrates all (or most) of these parameters and enables criticality and vulnerability levels to be categorized.

- Existence of **dams as singular structures** and their characteristics (type of dam, height, installed power, storage capacity, spillway capacity)

- **Type of project** (construction of new infrastructure or rehabilitation of an existing one)

- **Hydrological demand** (historical and projected maximum discharge values for the water course)

- **Proximity to human settlements** and other **critical infrastructure** (including both upstream and downstream populations and settlements)

- Impacts from a potential failure of the dam or spillway's pressurized pipes (population potentially flooded)

- Existence of **hydrogeology and seismicity**-related problems (i.e., variability of the hydrology, structural capacity, and permeability characteristics of the geology, slope instability conditions, or seismicity in the area).

To create this table, the following guiding dimensions were considered:

Scope of the subsector: Considering hydroelectric dams as a subsector is appropriate, and there is no need to disaggregate it further.

Relevant structures involved: Aside from the electrical systems and structures related to these projects, singular structures such as dams have significant weight in the project's criticality and vulnerability.

Relevant natural hazards: Hydrological hazards are clearly relevant for these infrastructures; however, others, such as earthquakes or geotechnical instabilities, are also pertinent because they can rupture the dam and cause an uncontrolled release of water.

Need to disaggregate key parameters into various tables: It is not considered necessary to create more than one table.

Key dimensions necessary: Three main dimensions were identified as encompassing all of the above-mentioned features: **loss of essential services, impacts on the population, and physical characteristics**.

The result from this thinking process led to the information contained in Tables 4.8, 4.9, and 4.10 and Box 4.11.

4.2.3.4 Social infrastructure

4.2.3.4.1 Brief description

For the purposes of this document, social infrastructure refers to education and health services, which provide communities or regions with vital functions on an ongoing basis. As such, it may be considered critical infrastructure since it should be planned, designed, and constructed to remain functional during and after a disaster. Typical social infrastructure includes the following:

- **Community centers and schools**, especially if designated as shelters or evacuation centers.
- **Medical facilities**, including hospitals, clinics, elderly housing, nursing homes, blood banks, and other health care facilities. Some of these facilities have occupants or residents who lack mobility and are thus more vulnerable during a natural hazard event.
- **Emergency response facilities,** including police stations, fire stations, critical vehicle and equipment storage facilities, and emergency operations centers needed for response activities before, during, and after a disaster.

Flooding can lead to inundation of lower floors; thus, movement of critical electrical infrastructure and logistic support (servers and data centers) to higher floors should be considered. Each of the essential systems of the social facility should remain intact or have backup systems to function before, during, and after the event. The building systems and equipment for social facilities should remain functional and be designed in accordance with local standards or the International Building Code (IBC). The loss of base support utilities can prevent some critical social facilities from functioning during and immediately after an event. Utilities are considered as part of social facilities if emergency backup systems are not in place to support the facility. An essential and enabling function for all social facilities is to remain connected with regional and national agencies for support. Box 4.11 illustrates the typical characteristics of a social infrastructure project that is considered in the Methodology.

Box 4.11. Social Infrastructure

4.2.3.4.2 Criticality and vulnerability chart

This subsector does not have a finished criticality chart like the previous three examples, but some preliminary and general guidance is provided here, along with examples of parameters that may be relevant to consider.

4.2.3.4.3 Support questions that guided the criticality and vulnerability discussion: Social infrastructure

Some examples of aspects that may be considered relevant to the discussion for assessing the criticality and vulnerability of social facilities, and which will help to arrive at the criticality table, are listed next. Discussions on these aspects with sector experts will lead to the creation of a table that integrates some of these parameters and allows a categorization of criticality and vulnerability levels. The information presented in Table 4.11 is drawn from internationally accepted best practices and best professional judgement.

Social Infrastructure (expert opinion provided by Tetra Tech)
(The thresholds are illustrative only and will vary depending on context.)

Table 4.11. Categorization of Criticality and Vulnerability in Social Infrastructure Projects

Key characteristics	Low	Moderate	High
Service area (km2)	<2	2 to 30	>30
Service population (capita)	<300	300 to 3,000	>3,000
Capacity of facility (people)	<50	50 to 500	>500
Size of building(s) (m2)	<100	100 to 3,000	>3,000

Key characteristics	Low	Moderate	High
Number of critical facility staff active during event	<10	10 to 50	>50
Communication methods	Extensive and redundant	Redundant	Limited

4.2.4 Outcomes of Phase I

The main output from this phase is a classification of the disaster and climate change risk for the project. This classification has three possible values: low, moderate or high. In determining this classification, aspects from the exposure of the project to natural hazards, the intensity of these hazards (Step 1), and the project's criticality and vulnerability (Step 2) should be considered and weighed using professional best judgement to arrive at an integrated appraisal of the risk conditions. Furthermore, if as a result of Step 2 and after considering of all aspects of risk there is a change in the preliminary classification provided by Step 1, then the Safeguard Screening Form needs to be updated accordingly to reflect the new classification.

This disaster and climate change risk classification forms the basis for the proportional and scalable process that follows as it provides a means to prioritize efforts and requirements involved in the execution of subsequent disaster and climate change risk assessments. Following this logic, and in accordance with the Disaster Risk Management Policy, if an operation is categorized as low risk, it may exit the process at this point, while all others must continue to Phase 2.

Finally, the objective of the screening process is to provide a **first** glance at the level of disaster and climate change risk of projects by looking at the three components of risk. This is done so that specialists and team members become **aware** of these risks and can preliminarily **identify** the natural hazards and characteristics of the project that they will need to pay attention to. Consequently, they can **begin** investigating these risks in further detail. This analysis, carried out for screening purposes, is by no means a final disaster and climate change risk assessment.

4.2.5 Example: Project Criticality and Vulnerability Assessment

4.2.4.1 Agricultural project

A project focusing on agriculture and innovation in agroforestry in the Caribbean was classified as High- riskas per Step 1 of the screening process since it was located in a country with high exposure to natural hazards including earthquakes, hurricanes and flooding, among others.[14] The project aimed to promote sustainable agriculture by offering agricultural technology packages. The technological packages consisted mostly of seeds and other small-scale tools (animal-traction carts) for field soil management; this project did not include large scale infrastructure irrigation works. Thus, when adding a lens of project criticality and vulnerability, and considering the fact that the project was not highly vulnerable to the hazards, the project classification was corrected as moderate risk.[15] This example shows how Step 2 serves as a correction of Step 1, which only covers one side of risk.

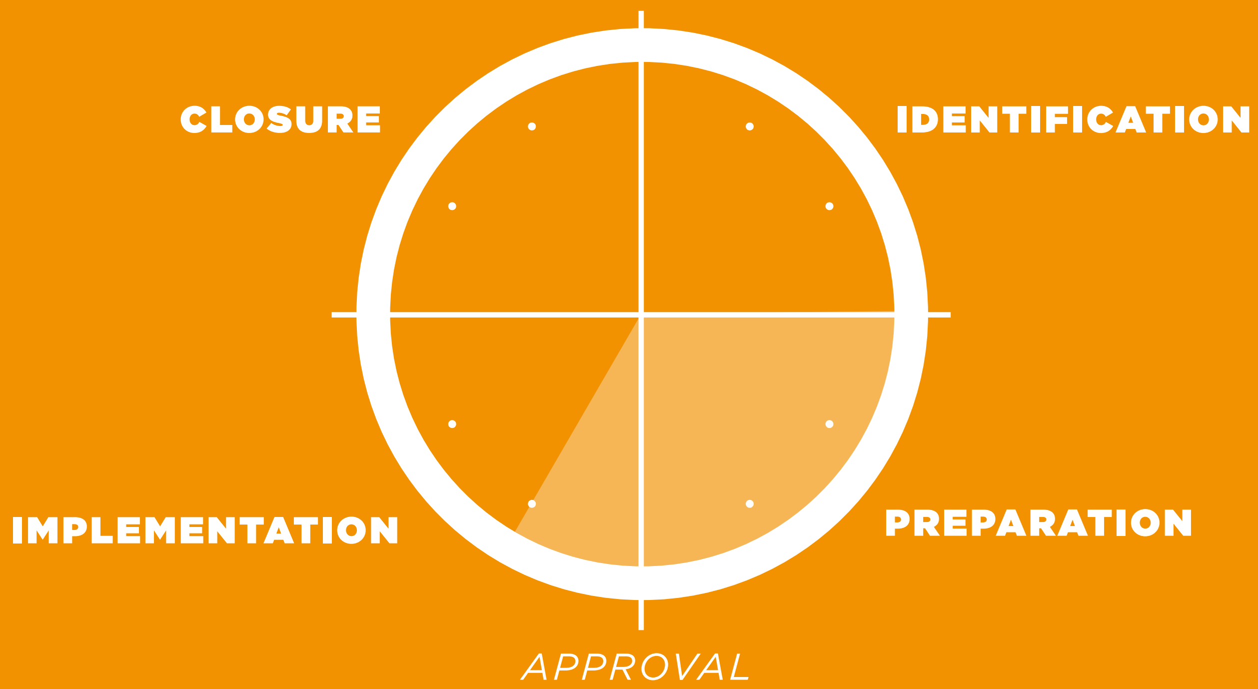
14 As per the Disaster Risk Management Policy Guidelines, "a project will typically be classified as high risk if one or more of the significant natural hazards may occur several times during the execution (construction) period and/or the operational life of the project and/or the likely severity of social, economic and/or environmental impacts in the short to medium term is major or extreme."

15 As per the Disaster Risk Management Policy Guidelines, a "project will typically be classified as moderate risk if one or more of the prevalent natural hazards are likely to occur at least once during the execution (construction) period and/or the operational life of the project and/or the likely severity of impact in the short to medium term is average. These impacts are typically confined to the project site and can be mitigated at reasonable cost."

5.

PHASE II: Qualitative Assessment

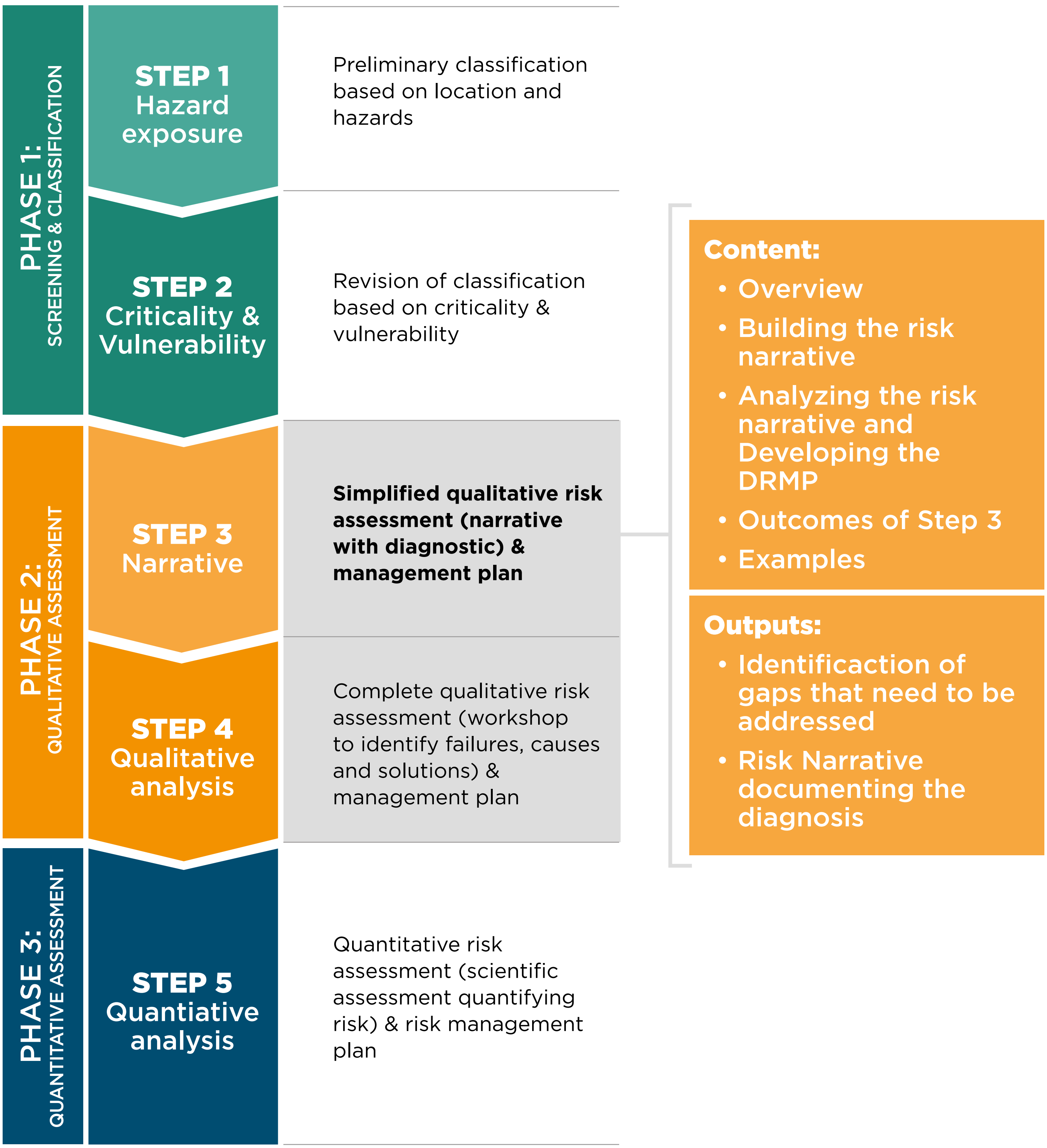
This phase should be conducted once there is more definition on the project. The first step should occur prior to approval (during the preparation stage), but the second step can occur during the early stages of implementation when the necessary project details are only known at a later point.



5. Phase II – Qualitative assessment

5.1. Step 3 – Simplified Qualitative Risk Assessment (Risk Narrative) and Risk Management Plan

Figure 5.1. Step 3



5.1.1 Overview

The third step in the Methodology consists of a diagnosis of the project conception in terms of disaster and climate change risk. It is the first step after the high-level screening that goes deeper into the project and begins investigating this theme in more detail.

This step must be carried out when there is basic (minimum) but specific information and knowledge of the project design. The purpose of Step 3 is to arrive at an initial, or simplified, qualitative risk assessment and to have it documented during project preparation, before the project is approved (although it could be updated later on when more information on the project design and/or other studies has been gathered).

In summary, this diagnosis aims to determine whether the existing (usually during early project preparation when the basic information is available) project conception includes considerations (if any) that are sufficient to reduce existing and future risks. This is documented through a short narrative, called the "risk narrative."

Only moderate-risk projects are given the option to finish and exit the Methodology at this step if certain conditions are met, whereas high-risk projects necessarily need to continue to Step 4, at a minimum (see Figure 5.1). This means, for moderate-risk projects, that if the risk narrative concludes that existing design considerations reduce or manage current and future risks at a tolerable level, then the project does not need to move to the next step. Conversely, if the risk narrative identifies gaps, that is, if the existing considerations are not sufficient or they leave out important aspects, then these need to be studied and the project should continue to Step 4 (as would high-risk projects).

To build this risk narrative and determine whether the project's current design and management plans would adequately mitigate the existing and future risks, two main tasks need to be undertaken. The first consists of collecting and analyzing existing hazard, vulnerability, and risk data, including climate change considerations, along with existing studies and risk management systems specific to the project or the area where the project is sited. The second consists of analyzing the collected data and determining if it is enough to mitigate the risk to both the project itself and the surrounding communities and environment (making sure pre-existing risks to third parties are not exacerbated).

5.1.2 Building the Risk Narrative

A set of questions may be prepared and shared with the project team and/or local counterpart (the project's executing agency) to guide the construction of the narrative. The answers to those questions should provide enough information to develop a risk narrative that states the existing information and how disaster and climate change risk is being addressed at the project level, and identifies the key gaps that need to be reviewed and need further analysis (and, if necessary, to move to Step 4).

5.1.2.1 Review of existing studies and reports addressing disaster and climate change risk

The first step when assessing risk in a project is to review relevant studies in the project area. To this end, the project team, with the support of a disaster and/or climate change specialist, should ask the executing agency and/or engineering team for any previous risk studies for the existing and/or proposed assets.

This review of existing reports and the relevant discussion with the executing agency should address all hazards that might affect the project. Sometimes one hazard is very well studied and included in the design, but other hazards affecting the project are not even considered. Therefore, it is very important to take into consideration all hazards affecting the project, the criticality and vulnerability of the proposed project, and the risk conditions in the surrounding areas.

In some cases, studies in the area of the intervention are already available (even if not specifically related to the proposed project), and there are some models or studies of the main hazards that affect the city, town, municipality, basin, or other geographic area. Existing studies may also gather relevant information on the characteristics of the community in the area, including its vulnerabilities.

It is also important to ask both the executing agency and the engineering firm if risk reduction measures have already been incorporated into the existing design. Sometimes they have already been considered because the proposed project follows international standards or existing building codes. In other cases, they were considered precisely because of existing studies in the project area that justify the adoption of such standards or other mitigation or preventive measures.

5.1.2.2 Inquire about relevant hazards

Table 5.1. includes guiding questions to ask when gathering information to prepare the risk narrative, classified by type of hazard. A second guide has been included to help in inquiring about the effect of climate change on these hazards (Box 5.1).

Table 5.1. Guiding Questions on Key Hazard Information

Hazard	How have the hazards been considered?	What parameters should the project design adjust to?
Coastal flood	· Have wave, tide, and water levels been assessed? · Has the coastline been characterized? · Have previous events been identified?	Has the project included flood extent, velocity, and depth as design parameters?
Riverine flood	· Has the hydrology been characterized? · Have the hydraulics been characterized? · Have previous events been identified?	Has the project included flood extent, velocity, and depth as design parameters?
Hurricane wind	· Has vegetation and surface roughness been recorded? · Have previous events been identified?	Has the project included wind speed as a design parameter?
Hurricane surge	· Have wave, tide, and water levels been assessed? · Has the coastline been characterized? · Have previous events been identified?	Has the project included flood extent, velocity, and depth as design parameters?
Tsunami	· Have wave, tide and water levels been assessed? · Has the coastline been characterized? · Have previous events been identified?	Has the project included flood extent, depth, and flux of tsunami as design parameters?
Landslide	· Has the slope been calculated? · Have the soil types been identified? · Has the vegetation and landcover been determined? · Have previous events been identified?	Has the project included areas of susceptibility as a design parameter?
Wildfire	· Have fuel sources been identified? · Has the meteorology been analyzed? · Have previous events been identified?	Has the project included areas of susceptibility as a design parameter?
Drought	· Has the meteorology been analyzed? · Have the water sources been identified? · Have previous events been identified?	Has the project included areas of susceptibility as a design parameter?

Hazard	How have the hazards been considered?	What parameters should the project design adjust to?
Volcano	• Have lava flow areas been defined? • Have previous events been identified?	Has the project included areas of susceptibility as a design parameter?
Earthquake	• Have soil types been identified? • Has the liquefaction potential been determined? • Has the ground motion been characterized? • Have previous events been identified?	Has the project included ground motion as a design parameter?
Heat Wave	• Has the meteorology been analyzed? • Have previous events been identified?	Has the project included areas of susceptibility as a design parameter?

Box 3.6. Asking about Climate Change Considerations in Project Design

Many types of hazards arise from the interaction of project design and severe weather events or abnormal climate conditions. Hazard analysis in engineering design is often based on empirical evidence obtained from past data with the assumption that the frequency of extreme events likely to be seen in the future can be inferred from the historical record. This implies that climate is stationary, an assumption that has been the foundation of infrastructure planning for decades. However, projected changes in future climate, which include the influence of anthropogenic activity, imply that the assumptions of climatic stationarity are no longer valid (Milly et al., 2008). Commenting on the "death of stationarity," Galloway (2011, p. 1) noted that "there is also a great need to provide those in the field the information they require now to plan, design, and operate today's [and tomorrow's] projects."

This step also involves determining whether climate change considerations were integrated into the hazard modeling or hazard assumptions. It is not enough to consider climatic hazards based on historical climate data alone; the availability of projected changes in climate should also be considered. The design team should be asked whether and how potential climate change was taken into consideration for the design relative to each hazard of concern. There may be different answers to this question for different climate change considerations. The following are some questions that can be asked to explore how climate change was analyzed:

- Was the level of protection determined through a standard engineering design process, such as the use of formal intensity, duration, and frequency (IDF) curves provided by local, state, or federal agencies or authorities?
- What opportunities were available during the design process to consider other climate information in the DRA?
- Did the design process allow for the use of alternative procedures such as revised IDF curves that reflect future climatic conditions based on an analysis/synthesis of climate model output? If so, examine the methods and approaches.
- Did the level of protection come from analysis based on detailed climate model outputs? If so, which ones and what data were used?
- What assumptions were made when selecting the climate model outputs, such as which representative concentration pathways (RCPs) were chosen? Global climate model projections make assumptions regarding future greenhouse gas concentrations, where higher emissions generally imply greater magnitudes of future climate changes.
- Were the climate model outputs downscaled to represent local conditions and adjusted to represent the time scale of interest (e.g., urban flooding analysis might require hourly rainfall projections)? If so, what was the method? Was a new downscaling analysis undertaken or were data used from an established repository?
- Were future climate projections developed or made available through the application of a downscaling procedure that was based on outputs from global climate models? What was the nature of the downscaling procedure and were the data adequately evaluated using sound scientific/statistical principles?
- Did the level of protection come from conclusions in a summary of regional climate projections, such as an IPCC report? If so, which summary and what data were used?
- Did the level of protection come from an expert recommendation? If so, what was assumed?

- Did the level of protection come from a previous DRA or other design process incorporating climate conditions in the local area? If so, which ones?
- Did the level of protection come from a worst-case climate project scenario? If so, describe the scenario and the justification for the scenario representing a true worst case under future climate conditions. What statistical methods were used to develop the new information?

A second factor to consider is the anticipated useful life of the project. A project for a temporary facility that will be removed from service after a few years probably does not merit as detailed a climate change analysis compared to one that is intended to be in use for several decades or more. Selection of the climate model and RCP should be noted.

See Appendix E for a brief overview of key climate change considerations and concepts.

5.1.2.3 Inquire into design considerations

In some cases, the engineering designs already consider the hazards that might affect the project. Sometimes the events that can recur are already known, or international standards are implemented as good practice, or national standards and codes required by law have been followed. Yet, in some cases, for some hazards it is necessary to go beyond that. When designing infrastructure that is resilient to seismic events, engineers might use the national building code. In some countries statutory regulations are very strict while in others the codes are outdated. For this reason, it is advisable to review which codes are proposed for the design.

To include other types of hazards in the design, like flooding, for example, further investigation on the hydrologic and hydraulic parameters is required. For those parameters, it is important to know which analysis methods have been used, what design return periods were considered for the analysis, and whether a flood frequency analysis was performed. It is also important to ask if climate change has been incorporated in the analysis, and if so, how. Also, it is important to ask if IDF curves that incorporate climate change have been included in the design.

In case the project is affected by landslides, it is important to ask if any slope stabilization measures were incorporated as part of the design, and how. Other hazards affecting the project might also need to incorporate climate change considerations. These include heatwaves, wildfires, or in case the project is located in a coastal area or in riverbanks, sea level rise or inland flooding, respectively. The **Quantification of the hazard component** section under Step 5 shows how to incorporate climate change in different hazard types.

Additionally, it is important to find out more about non-structural risk management measures, specific standards, regulatory instruments, planning tools (such as land ordaining plans), and response systems because, although incorporating disaster and climate change risk in project design could address a significant share of the risk, it is not necessarily able to reduce the risk to zero, leaving residual risk. This does not reflect a poor design; it is related to the tolerable risk level that any design assumes inherently in the use of design standards and return periods. This means that additional non-structural measures, such as early warning systems among others, and response systems may be needed to address this residual risk. Within response systems, it is important to inquire about any exiting contingency, emergency response, and business continuity plans in place for all project phases—construction, operation and closure of activities. Hence, the analysis should find out if any of these are already in place in the project area for each of the hazards that may affect the project.

Moreover, it is necessary to know which entities are responsible for emergency management in the area and their capacity. There may already be a local institution responsible for this, such as an emergency response center, or there may be a system that coordinates the responses of multiple agencies to address an emergency. Having a complete map of the actors involved and their capacity is extremely important to know and understand the limitations of a project when it comes to facing an emergency during its construction and operation. Identifying the types of instruments mentioned above and the entities responsible is helpful to identify existing governance and local capacity, as well as to consider when designing a disaster risk management plan.

5.1.2.4 Inquire about incremental risk

In some cases, the project location or its characteristics can pose additional risk to the surrounding communities and the environment. In the Risk Narrative, it is important to gather information regarding this incremental risk. The project team should ask and analyze, together with the executing agency, whether the project could exacerbate the risk posed by any of the identified hazards (with respect to the baseline) through an aggravation of the hazard, exposure, or vulnerability conditions.

The project itself can change the exposure conditions of its direct and indirect area of influence. Its presence may result in a significant increase in risks to the population or their assets, and they could end up being more exposed to natural hazards. Sometimes the presence of the project may result in increased vulnerability to workers, the community, and the environment to a hazard event.

Table 5.2 provides examples of how the project can aggravate the risks that may impact the project, the environment, workers, or the community. Some project activities are linked to specific hazards. For instance, removing vegetation from an area might lead to greater vulnerability and exposure to flooding, landslides, or wind damage.

Table 5.2. Potential Ways in which Project Activities and Components Might Intensify Risks

Project type	Project component	Examples
Water utility	Water treatment plant	• Vegetation removal may exacerbate flooding, landslides, and wind damage from hurricanes. • Use of impervious surfaces may exacerbate flooding and increase heat island effects. • Mechanical equipment and ancillary equipment or supplies can become projectiles/debris during strong storm winds. • Tanks and other large equipment could become mobile and destructive to other property during storm surge or tsunamis.
	Storage tank	• Failure, rupture, or overflow of storage tanks could result in a small-scale limited flood event to nearby facilities or structures.
	Distribution network	• Water main breaks could result in small-scale limited flood event to nearby facilities or structures.
	Instrumentation and controls	• Electrical equipment can become a shock hazard during floods or strong winds.

Project type	Project component	Examples
Wastewater utility	Wastewater treatment plant	· Vegetation removal may exacerbate flooding, landslides, and wind damage from hurricanes, and increase heat island effects. · Use of impervious surfaces may exacerbate flooding and increase heat island effects. · Mechanical equipment and ancillary equipment or supplies can become projectiles/ debris during strong storm winds. · Tanks and other large equipment could become mobile and destructive to other property during storm surge or tsunamis. · Untreated wastewater overflows during floods can spread pathogenic organisms, exacerbating public health risks. · Discharging wastewater effluent, instead of reusing it, can exacerbate water scarcity, particularly during droughts.
	Lift station	· Untreated wastewater overflows during floods can spread pathogenic organisms, exacerbating public health risks.
	Septic field	· Tree removal may exacerbate flooding and wind damage from hurricanes.
	Sewer network	· Tree removal may exacerbate flooding and wind damage from hurricanes. · Sewer lines can act as conduits for flood waters (mixed with sewage) to enter dwellings and other buildings without proper backflow protection.
Drainage	Stormwater network	· All stormwater systems can clog and cause flooding if not properly and regularly maintained. Cisterns and Tree Boxes are the biggest liability because they are usually implemented next to a building. · Stormwater infrastructure that is flooded or not properly maintained can pose risks to human health (vector and water-borne diseases) and safety (drowning).
Transporta-tion	Asphalt road	· During expansion of a highway, slopes may need excavation, including vegetation removal, which may exacerbate landslides and have other effects (drainage). · Use of impervious surfaces may exacerbate flooding risk.
	Bridge/culvert	· Should a bridge be poorly designed with insufficient freeboard, this may restrict flow and accumulate debris, exacerbating flood and debris hazard. · Water levels could rise upstream if opening is not adequately sized, causing flooding. Similarly, downstream structures and water levels need to be considered (i.e., if they are designed to a lower return period).
	Walls/embank-ments	· Retaining walls can cause significant property damage and/or fatalities both outside and inside the roadway right-of-way in the event of a failure. · Embankments can cause damage to adjacent property through deposits of eroded soil or through rock fall from steep rockfill slopes. · Significant fill slope erosion can occur when culverts become plugged, water overtops the roadway and causes sudden and extensive erosion into the fill on the downslope side of the embankment. · Embankments with inadequate drainage can dam surface water runoff on one side, causing temporary or long-term flooding of agricultural/forested land, resulting in economic losses. · Roadways built across ancient landslides can initiate slow creep-type movements of large block(s) of soil which can impact adjacent properties through breaking of buried utilities, constant cracking of roads and buildings adjacent to the roadway. The sudden failure of such embankments can cause extensive property damage and loss of life.
	Tunnel	· Excavation of a tunnel may alter the hydrogeological regime potentially affecting wells or water courses. · Subsidence from poorly constructed tunnels may cause differential settlement and affect the integrity of structures above the tunnels either in the ground or on surface as well as landslides.

Project type	Project component	Examples
Hydroelectric and irrigation	Dams/large water retaining structures	Many hydropower schemes require major retaining water structures, typically a dam (it can span from small overflow dams to large dams creating a big reservoir upstream) which are subjected to hydrological, seismic and landslides (in the reservoir) hazards, as well as inherent failure mechanisms driven by geological features, design deficiencies, construction issues, operation failures, lack of maintenance, etc. All these can result in uncontrolled and potentially catastrophic release of water, which can significantly affect properties, environment and cultural goods as well as human lives. • Construction of a new dam may change the risk profile for communities downstream, which may now suffer larger flooding in the event of a dam break, even though the probability is low. • During construction, temporal structures used to divert the water flow may fail due to extreme hydrometeorological events and may flood nearby communities.
	Pressurized piping system, Penstock, Turbines, and Connection to Electric Grid	• A failure in either the "water line", the "turbines" or the "connection to the grid" may interrupt energy generation and may be responsible of a black out (in the worst case even national or transnational) and it may also imply a significant reduction in discharge capacity with the potential of worsening any hydrological severe event (decreasing the dam safety margin)
Social infrastructure	Facility	• Vegetation removal may exacerbate flooding, landslides, and wind damage from hurricanes and increase heat island effects. • Use of impervious surfaces may exacerbate flooding and increase heat island effects. • Mechanical equipment and ancillary equipment or supplies can become projectiles/debris during strong storm winds. • Health supplies and waste (including hazardous waste) may be released (water or airborne) during a hazard event, exacerbating public health risks.

5.1.3 Analyzing the Risk Narrative and Developing a Disaster Risk Management Plan (DRMP)

5.1.3.1 Analyzing the Risk Narrative

Based on the information collected in the previous sections, all the findings should be summarized, clearly identifying what has been done and needs no further consideration, as well as any gaps and a recommendation on a course of action to address them. The current design and possible existing measures should be evaluated to determine if they are adequate.

5.1.3.1.1 Illustrative examples of risk tolerability standards based on international good practice

The general thresholds and criteria included in the tables that follow can be used to guide the thinking process to determine whether the mitigation measures found to exist in the project's design are adequate. These standards are provided for the project types identified before. These standards are considered good practices taken from international practice and not mandatory guidelines.

This information should be used to help determine whether the measure is adequate to mitigate the risk. Tables 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8 are for illustrative purposes only and are not meant to reflect IDB policy or practice. Team leaders should consult with the design team, as well as independent engineers.

Table 5.3. Social Infrastructure

Hazard(s)	Illustrative critical thresholds and criteria
Flood, surge, tsunami	• All social infrastructure, including access roads, should be designed to be protected to at least the 100-year flood elevation or maximum flood of record. The local regulatory authority may establish a freeboard factor (such as 600 mm).
Drought	• Social infrastructure should locate and secure an alternate supply of water if its normal water supply can be interrupted (municipal water network or on-site well). Critical care facilities should consider the feasibility of installing temporary water storage tanks or stockpiling bottled water.
Earthquake	• Social infrastructure and buildings should be designed and built to withstand the minimum seismic force as set forth in the local requirements or the International Building Code (IBC).
Hurricane wind	• Water utility structures and buildings should be designed and built to withstand the minimum wind loads as set forth in the local requirements or the IBC.

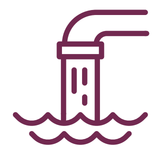


Table 5.4. Drainage Infrastructure

Project component	Hazard(s)	Illustrative critical thresholds and criteria
Conveyance, storage capacity, and peak flow	Flood	• Treatment systems should be designed to convey the 100-year flood event. Flow and volume above the design requirements should safely bypass the system up to the 100-year event.
Conveyance and storage	Hurricane wind	• Collection and conveyance systems structures and buildings should be designed and built to withstand the minimum wind loads as set forth in the local requirements or the IBC.
	Earthquake	• Collection and conveyance systems structures and buildings should be designed and built to withstand the minimum seismic force as set forth in the local requirements or the IBC.
All structures	Flood, storm surge, tsunami	• All drainage structures should be designed to be protected to at least the 100-year flood elevation or maximum flood of record. The local regulatory authority may establish a freeboard factor (such as 600 mm).

Table 5.5. Roadway Infrastructure

Project component	Hazard(s)	Illustrative critical thresholds and criteria
All structures	All	• Designed to national/local building codes that are considered appropriate for the hazard. More stringent codes used beyond the minimum national/local codes includes the American Association of State Highway and Transportation Officials (AASHTO) or Federal Highway Administration (FHWA) standard as appropriate for traffic levels and speed.
	Flood, hurricane surge, tsunami	• Typically, culvert and bridge crossings should be designed to withstand a 100-year flood event, i.e., a flood with a probability of occurrence of 1% on any given year. This event will need to be related to a critical design condition, such as maximum water level, maximum flow velocity, or/and maximum flow; whichever are the most relevant for the design. The critical condition will need to consider, where appropriate, boundary conditions that may impact the performance of the crossing structure, such as downstream water levels, for instance in a coastal environment. The design should be estimated based on projected climate change conditions, selecting the criticality of the emission scenario based on the relevance of the particular road.

Table 5.6. Wastewater Utility

Project component	Hazard(s)	Illustrative critical thresholds and criteria

• Lift station lids
• Manhole lids
• Valve box lids
• Tank/basin openings
• Electrical components
  • Controls
  • Blower motors
  • Dry pumps/motors
	Flood, storm surge, tsunami	• All components listed should be located above the 100-year flood elevation, considering projected sea level rise.
		• Where components cannot practically be located above the 100-year flood elevation, they must be watertight or protected (e.g., by a physical barrier).
		• Above-grade structures located in areas subject to hazard must be designed to withstand differential hydrostatic loads and loads associated with surge or tsunami.
		• All structures should undergo anti-buoyancy evaluation and design for designated water level.
		• Corrosion-resistant materials (PVC/plastic, iron, or stainless steel for metal components) should be used.

• Structures (tanks, buildings) • Pipes	Earthquake	• Structural reinforcement and foundation in accordance with appropriate seismic design standards. • Use flexible pipe joints and penetrations into tanks to prevent breakage due to differential movement.
• Electrical and mechanical equipment • Pipes and underground infrastructure	Hurricane wind	• Provide backup power sources as practical (minimally, emergency generators, but preferably reliable renewable energy source) • Provide excess storage capacity (as much storage as required for time that power is expected to be down) throughout collection system and treatment system to allow wastewater to be stored when treatment system is down.

Table 5.7. Water Utility

Project component	Hazard(s)	Illustrative critical thresholds and criteria
All water utility components	Flood, tsunami, surge	• Other than surface water intake structures, all water supply facilities and water treatment plants and access roads should be designed to be protected to at least the 100-year flood elevation level or maximum flood of record. The local regulatory authority may establish a freeboard factor, such as 600 millimeters (mm).
Surface water supply	Drought	• The demand on the surface water supply should consider the demand of the water utility and be adequate to provide ample water for other legal users (water rights) of the source. • The capacity on the surface water supply should consider a reasonable surplus for anticipated growth (20+ years) • The capacity of the surface water supply should be adequate to compensate for all losses such as silting, evaporation, and seepage. • The surface water should be adequate to meet the maximum projected water demand of the service area as shown by calculations based on a 1-in-50-year drought or the extreme drought of record, and should include consideration of multiple year droughts. • The withdrawal impacts by the water utility and other uses should include consideration and meet any regulatory requirements to maintain flows downstream of the intake to comply with minimum stream/aquatic base flow requirements (for environmental or navigational purposes). • If adequate capacity remains available during drought conditions, an assessment should be conducted to project if the water quality during a shortage is expected to differ from normal conditions.
Ground water supply	Drought	• The capacity of the groundwater supply should be determined to the extent possible based on worst case conditions (projected or actual). • The well capacity test should be conducted with a test pump that has a capacity at least 1.5 times the flow anticipated at maximum anticipated drawdown. • The well capacity test shall provide, as a minimum, for continuous pumping for at least 24 hours at the design pumping rate or until stabilized drawdown has continued for at least six hours when pumped at 1.5 times the design pumping rate. • The well will be considered stable during the test when water level fluctuation is less than 50 mm over the final four hours of the pumping test. • The well may also be considered stable during the test when using a semi-logarithmic plot extrapolation of the time-drawdown curve derived from the pumping test and projected over a 180-day period, 10 percent of the water column between the top of the pump and the static water level remain and a minimal submergence of 5 m for bedrock wells and 1.5 m for overburden wells. • If adequate capacity remains available during drought conditions, an assessment should be conducted to project if the water quality during a shortage is expected to differ from normal conditions.
Water utility structures	Earthquake	• Other than surface water intakes structures, all water supply facilities and water treatment plant, access roads should design to be protected to at least the 100-year flood elevation or maximum flood of record. A freeboard factor (such as 600 mm) may be established by the local regulatory authority.
Water utility structures	Hurricane wind	• Other than surface water intake structures, all water supply facilities and water treatment plant access roads should be designed to be protected to at least the 100-year flood elevation or maximum flood of record. The local regulatory authority may establish a freeboard factor (such as 600 mm).

Table 5.8. Hydropower

Project component	Hazard(s)	Illustrative critical thresholds and criteria
Dams and reservoirs (including bottom outlets, spillways, etc.)	Flood, Earthquake, Landslide	· Dams and reservoirs, particularly those that fit into the International Commission on Large Dams (ICOLD) category of large dams (total height beyond 15 meters or between 10 and 15 meters retaining a volume higher to 3 millions of cubic meters) have a significant number of standards to meet that are considered best practices as well as quantitative risk guidelines. · The standards include the whole life cycle (design, construction, operation and decommissioning) and are very extensive. Some of them can be highlighted to illustrate the required level of safety with regard to main natural hazards: · Large dams whose failure may cause loss of life (the vast majority of them) should safely pass the 5000 -10000 return period flood depending on their typology, or the so called Maximum Probable Flood, depending on the code approach (probabilistic or deterministic) · Similar levels are required for these dams in highly seismic areas, and they scale down in the case of moderate seismic areas. · From the point of view of quantitative risk, main available references (ANCOLD 2003, USBR 2011, SPANCOLD 2012, USACE 2014, or CWC-INDIA 2018) suggest 10-4 as tolerable threshold for annualized individual risk (typically equivalent to total probability of failure for these type of structures) and 0,001 lives per year as reference threshold for incremental societal risk (this varies as function of total expected live losses and it is normally truncated at 1000 lives) · In addition, regulations of dam safety make, in most cases, mandatory to maintain a Dam Safety File with all updated information influencing dam safety, an approved, written and operative Emergency Action Plan, as well as clear and fully documented Operating Rules, in addition to periodical reports on Monitoring and Performance and Periodical Comprehensive Dam Safety Evaluations. · Many international codes (i.e. all Spanish regulations since 1967) require providing bottom outlets (a minimum of two) to have effective water pool level control, not allowing to rely exclusively in the discharge capacity of the turbines (neither accounting for turbine discharge capacity during floods)

5.1.3.2 Developing a Disaster Risk Management Plan

The final step to conclude a good risk narrative is translating the gaps and next steps from the narrative into a Disaster Risk Management Plan (DRMP). This plan should include a clear action plan detailing how to address the gaps identified, including a possible recommendation to continue to Step 4 and conduct further studies. In some cases, it may be possible to propose some risk reduction measures directly (if there are no significant gaps). These would typically include green measures (such as ecosystem-based adaptation) and non-structural measures related to response systems, such as early warning systems (EWS) and other measures that are part of contingency, emergency response, and business continuity plans that help to reduce the potential impacts during construction and operation phases of the project. The DRMP could be a hybrid of all aspects listed above. The measures set forth in the DRMP must include a hierarchy defining the different levels or priority.

5.1.3.2.1 Indicative mitigation measures

To assist in the preparation of the proposal of new or additional measures for the DRMP, Table 5.8 lists typical examples of disaster risk mitigation and climate change adaptation for the project types described in Step 2. This is for illustrative purposes only and not meant to reflect IDB policy or practice. The design team should be consulted before any measures are proposed.

Table 5.8. Examples of Disaster Risk Mitigation Measures

Project type	Hazard(s)	Examples of disaster risk mitigation measures
Water utility	Flood, tsunami, surge	• Siting outside/above 100-year flood elevation and consider re-evaluating under climate change • Use waterproof covers and lids over manholes and tank openings • Use submergence-proof electrical control and junction boxes • Use submersible mechanical components (e.g., submersible pumps) • Proper anti-buoyancy provisions (e.g., anchors where needed) for underground tanks • Site critical system components outside/above local surge zone • Ensure positive drainage at sites hosting critical system components
	Earthquake	• Water treatment plant, dams, buildings, structures, process tanks, and storage tanks design to be developed based on the seismic conditions documented in the International Building Code and local codes. • Water transmission mains to be designed with flexible joint, e.g. avoid rigid joints, and materials, e.g. high-density polyethylene (HDPE), when available.
	Drought	• Redundancy in supplies (e.g., interconnections to other utilities, surface and groundwater, water reuse technologies).
Wastewater utility	Flood, tsunami, surge	• Siting outside/above 100-year flood elevation • Use waterproof covers and lids over manholes and tank openings • Use submergence-proof electrical control and junction boxes • Use submersible mechanical components (e.g., submersible pumps) • Proper anti-buoyancy provisions (e.g., anchors where needed) for underground tanks • Site critical system components outside/above local surge zone • Ensure positive drainage at sites hosting critical system components
	Earthquake	• Design structures per local earthquake load standards or IBC and local codes if appropriate • Ensure proper/secure bedding of pipes, valves, tanks • Use flexible, watertight, resilient tank/basin penetrations
	Hurricane wind	• Design of structures per local wind load standards • Use multiple zones for irrigation/land application systems to facilitate system isolation when tree blowover exposes or breaks distribution piping • Ensure sufficient isolation valves in collection/conveyance systems to facilitate repairs when tree blowover pulls up piping • Ensure vulnerable treatment facilities/components are protected from flying debris • Some mitigation measures to reduce the risk of loss of power include: Emergency gas- or diesel-powered generators at all critical facilities Less reliance on mechanical systems (e.g., use more passive treatment systems) Provide excess storage in collection system or at treatment system
	Drought	• Maximize water reuse and/or irrigation to recharge aquifers
	Volcano	• Site critical system components away from areas that may be impacted • Raise access to underground system components (e.g., lift station) to ensure they will be accessible with lava and debris

Project type	Hazard(s)	Examples of disaster risk mitigation measures
	Wind	• Bridge design is suitable for wind loading conditions to a given design event with appropriate projected future return periods. • Rock fall induced by wind is mitigated by effective catchment or other control measures.
	Flood	• Typically, culvert and bridge crossings should be designed to withstand a 100-year flood event, or an event with a probability of occurrence of 1 percent in any given year. The design should be estimated based on project climate change conditions, and possibly consider identification of alternative roads in case of failure.
	Earthquake	• Roadway components are designed for appropriate projected future return periods. Design for appropriate level of resiliency. • North American standards such as the American Association of State Highway and Transportation Officials (AASHTO) typically use a 1 in 2,475-year return period for a seismic event.
Social	Flood, tsunami, surge	• Designed to the 100-year flood elevation or maximum flood of record. The local regulatory authority may establish a freeboard factor (such as 600 mm). Consider updating this event and factors periodically.
	Earthquake	• Designed to withstand the minimum seismic force as set forth in the local requirements or the IBC.
	Hurricane wind	• Designed to withstand the minimum wind loads as set forth in the local requirements or the IBC.
	Drought	• Locate and secure an alternate supply of water (municipal water network or on site well). • Consider the feasibility to installing temporary water storage tanks or stockpiling bottled water.
Drainage	Earthquake	• Avoid areas of liquefaction.
	Hurricane wind	• Implement vegetation support and tie downs
	Flood, tsunami, hurricane surge	• Increase flood control capacity or overflow structures • Ground cover displacement • Plant vegetation adapted to prolonged inundation • Plant vegetation adapted to potential increased salinity • The BMP implemented should use a combination of native wetland plants and stone or rock structures
	Drought	• Use drought-tolerant vegetation or provide irrigation.
Hydropower (dams and reservoir component)	Flood, Earthquake, Landslide	• Main structural measures are related to: Increased capacity of river diversion structures during construction Upgraded spillway capacity Reliable and redundant hydro-mechanical equipment (gates, valves, etc.), Stabilizing the reservoir against land-sliding Foundation treatments against excessive permeability or deformability A major change of the dam body and or spillway typology any of the previous issues and/or for the need of better seismic response. • Main non-structural measurements are linked to ensure: A number of significant monitoring devices are installed in the dam (depending on the type of dam and foundation they may be leaking meters, piezometers, inclinometers, pendulums, topographical items, etc.) Hydrometeorological devices in the basin and seismic devices in the dam and surrounding foundation • All devices needed to operate during extraordinary events such severe floods and to issue alarms under emergency scenarios.

5.1.4 Outcomes

The overall objective of the Risk Narrative is to have a preliminary summary or diagnosis that documents how disaster and climate change risk has already been addressed in the IDB operation. It should be an official IDB document included as an Annex of the Proposal of Operation (POD). This document is mandatory for all projects classified as moderate and high risk. As stated before, if at the time the Risk Narrative is prepared there is not enough detailed information on the project design, then the Risk Narrative should document the limitations when the narrative was written and identify the hazards or other relevant aspects that have been well studied. It should also identify the information gaps in the analysis of specific aspects that need further study in the next step (Step 4).

The content of the Risk Narrative should be discussed with the executing agency and the engineering team responsible for the project's design, as well as with members of the Community of Practice on Resilience that are supporting the project team in the process of compliance with the Disaster Risk Management Policy.

The Risk Narrative should help to determine if the project team has gathered enough information on the risks that might affect the project and how the project design and additional measures have addressed them. If the project has been classified as moderate risk and based on the information compiled in the Narrative it is determined that the existing measures are sufficient, then the analysis may stop in this step, and making the Risk Narrative the DRA for the project. However, if the Narrative for the moderate-risk project shows that it has not covered and adequately addressed the most important risks, then it should proceed to the next step. If the project has been classified as high risk, then the next step is mandatory.

5.1.5 Example 1: Risk Narrative for Road Infrastructure

The following questions were used to construct a disaster and climate change risk narrative for a road project in an urban setting where the city had already identified mudslides and flooding as the critical hazards.

Existing studies and measures

1. What are the main hazards of concern and are there any previous risk studies for the road? (Have the impacts from hazards on the project been assessed? Have the impacts from the project on the risk conditions in the surrounding area been assessed?)

2. Are there any previous risk studies for the study area, including the communities in the area? (Have the impacts from hazards on the area been recorded and assessed?)

3. Do risk reduction measures for relevant hazards already exist or are they planned to be implemented in the project area?

4. Is there redundancy in the roadway system that would allow the transportation service to continue in the area if the road under study fails?

Hazard evaluation

Earthquake hazard

1. Have the local geology and seismicity been characterized and, if so, how? (Does the road cross active faults? It there a seismic catalogue for the area?)

Mudslide hazard

2. Has the local meteorology and hydrology for the basin of interest been studied, and, if so, how? (Are there gauge data?)

3. Have the slopes of the mountainous section of the road been studied for stability?

Hydrometeorological hazard

4. Have the effects of climate change on local meteorology and hydrology been studied, and, if so, how? (Have global/regional climate models been consulted for climate change projections? Are there official standards for the use of climate projections? Have the existing climate projections been verified?)

Design considerations

1. What are the hydrologic and hydraulic parameters used for the designs of bridges and longitudinal and transversal drainage structures? (Analysis methods, design return periods, flood frequency analysis? Has climate change been considered and, if so, how? Are there official IDF design curves?)

2. What seismic design standard has been used for the design of bridges? (Is there a local design code?)

3. Have any slope stabilization measures have been considered for the mountainous section of the road?

4. Has the effect of climate change been considered in the pavement design of the road?

Management and response systems

1. Is there an early warning system in place in the project area or is one planned for precipitation, flooding, and mudslides?

2. Does a program, normative, or regulatory instrument exist for the management of the river basin?

3. Has a contingency plan been developed to ensure the continuation/rapid recovery of the service provided?

4. Is there a local institutional entity or system that centralizes the management of disaster risk?

5.1.6 Example 2: Risk Narrative for Drainage and Water and Sanitation Infrastructure

The following questions may be used to construct a disaster and climate change risk narrative for a drainage or water and sanitation project.

Existing studies and measures

1. Are there any previous risk studies for the existing assets (if any)? (Have the impacts from hazards on the project been assessed? Have the impacts from the project on the risk conditions in the surrounding area been assessed?)

2. Are there any previous risk studies for the geographic area (neighborhood, city, town, municipality, basin, etc.), including communities in the area? (Have the impacts from hazards on the area been assessed?)

3. Do risk reduction measures for relevant hazards already exist or are they planned to be implemented in the project area?

Hazard evaluation

4. What are the main hazards of concern, including both hydrometeorological and geophysical hazards? For each of the identified hazards of concern, use the following guiding questions.

Earthquake hazard

5. Have the local geology and seismicity been characterized and, if so, how? (Do the networks and/or reservoirs cross active faults? It there a seismic catalogue for the area?)

Flooding hazard

6. Have the local meteorology and hydrology for the basin(s) of interest been studied, and, if so, how? (Is there gauge data?)

7. Have the effects of climate change on local meteorology and hydrology been studied,

and, if so, how? (Have GCM/RCM been consulted for climate change projections? Are there official standards for the use of climate projections? Have the existing climate projections been verified?)

Hurricane storm surge hazard

8. Has the coastal tidal and surge regime been studied and, if so, how? (Have models been developed? Have data from past events been studied? Has the effect of climate change been considered?)

Landslide hazard

9. Have the existing slopes around critical infrastructure (particularly around treatment plants and water retaining structures - reservoirs) of the systems been studied for stability?

Sea level rise hazard

10. Have the effects of climate change on sea level rise been studied, and, if so, how? (Have global/regional climate models (GCM/RCM) been consulted for climate change projections? Are there official standards for the use of climate projections? Have the existing climate projections been verified?) and/or form the selection of a "worst-case" projection? If so, which one(s)?

11. Did the level of protection come from a set of GCM projections and/or from the selection of a "worst-case" projection? If so, which one(s)?

Tsunami hazard

12. Has the coastal wave regime been studied and, if so, how? (Have models been developed? Has data from past events been studied?)

Volcanic hazard

13. Have the lahar paths been studied and, if so, how? (Have models been developed? Has data from past events been studied?)

Vulnerability

14. What is the existing exposure in the project's direct and indirect area of influence (population and assets exposed and their value)?

15. What are the vulnerability conditions of the exposed elements toward the different natural hazards (asset vulnerability, i.e., construction type, materials, overall quality and state; population vulnerability)?

Design considerations

16. What are the hydrologic and hydraulic parameters used for the designs of water retaining structures (dams, reservoirs, levees, etc.)? (Analysis methods, design return periods, flood frequency analysis? Has climate change been considered and, if so, how? Are there official IDF design curves?)

17. What seismic design standard has been used for the design of water retaining structures (dams, reservoirs, etc.), treatment plants, and administrative buildings? (Is there a local design code?)

18. Have the design and systems incorporated cost-effective and appropriate available materials and technologies that consider the hazards?

19. Does the project design already consider avoiding/minimizing/mitigating risk to surrounding communities? How? To what extent?

20. Which data and hazard model was used to define the level of protection in the design?

21. Does the level of protection in the design come from an expert recommendation or from an international or national standard? If so, what was the standard and what was assumed?

22. Does the level of protection come from previous designs in the local area? If so, which ones?

Response systems

23. Is there an early warning system in place in the project area or is one planned for precipitation and flooding?

24. Has a contingency plan been developed to ensure the continuation/rapid recovery of the service provided?

25. Has an emergency plan been developed to define roles, responsibilities, and activities to prepare for an emergency?

26. Does the drainage or water and sanitation system have redundancy? (Redundant pipeline networks, reservoirs in treatment plants, machinery, connections, etc.?)

Incremental risk

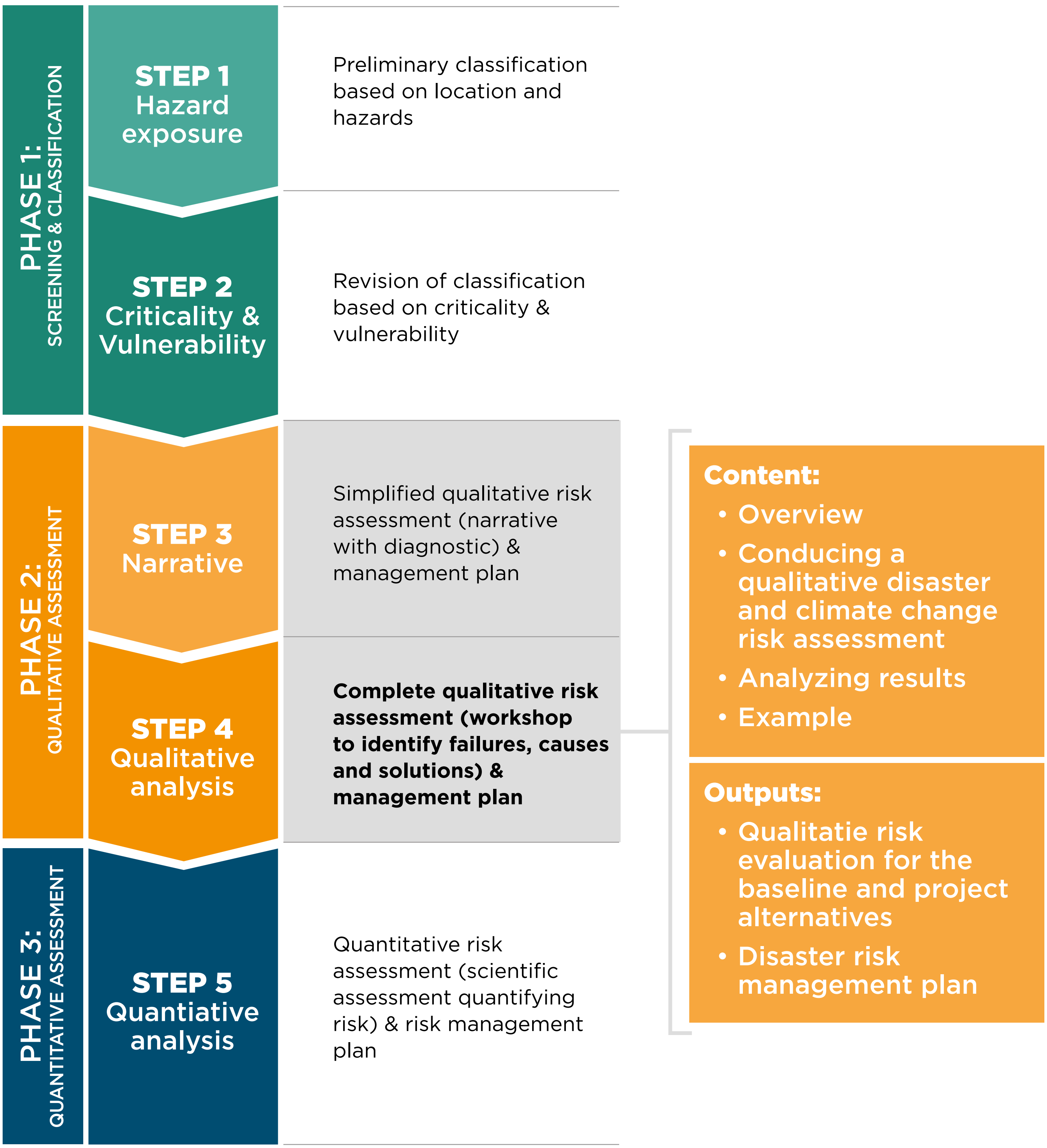
27. Could the project change the hazard conditions (e.g., frequency, intensity, spatial extent) of any of the identified hazards, resulting in increased hazard levels (with respect to baseline conditions)?

28. Could the project change the exposure in its direct and indirect area of influence resulting in a significant increase of the assets or population that will then be exposed to natural hazards?

29. Could the operation change the conditions of vulnerability of the exposed elements and surrounding communities to natural hazards, resulting in an increase in vulnerability?

5.2. Step 4 – Complete Qualitative Risk Assessment and Risk Management Plan

Figure 5.2. Step 4



5.2.1 Overview

Step 4 involves performing a complete qualitative risk assessment for all high-risk projects, as well as for those moderate-risk projects that were determined to need it in the previous step (where the Risk Narrative identified critical gaps that need further treatment). By first qualitatively evaluating all risks, the need for a detailed quantitative assessment can be easily determined and targeted to cover only the specific parts of the operation and topics that require it. This step also includes a disaster and climate change risk management plan for those risks and features of the operation for which the necessary measures can be identified through the qualitative analysis. Operations where the qualitative analysis and its corresponding risk management plan fail to solve large uncertainties or are not sufficient to get to a tolerable level of risk (there are still risks and features of the operation that could compromise the technical and/or economic viability or pose a high risk to the project itself or surrounding communities) must continue to the next step in Phase 3 to quantify those uncertainties or critical risks.

The application of qualitative analysis tools leads to: (i) an overall classification and specific sub-classifications by categories of the risks (project-specific: it should not be confused with the screening and classification done in Steps 1 and 2); (ii) an identification of the causes and consequences of such risks; (iii) an identification of required mitigation actions that need to be adopted in the short and long term; and (iv) a determination of any further quantitative risk analyses that could be required, and how and where to focus them. A qualitative analysis includes expert opinions, intelligence information, systematic team approaches, and inductive reasoning techniques, among others (European Commission, 2010) (quantitative methods, instead, enable values to be assigned to the risk components—probability and consequences—to estimate the existing risk and evaluate the impact on risk of mitigation measures).

There are different techniques to conduct a qualitative analysis, including conducting a failure-modes analysis, conducting consultations to a select panel of experts, or using risk matrices. The choice of method will depend on the type and size of the project and infrastructure to be analyzed. The following section will provide more detail on how to conduct a qualitative analysis using these three methods.

5.2.2 Conducting a Qualitative Disaster and Climate Change Risk Assessment

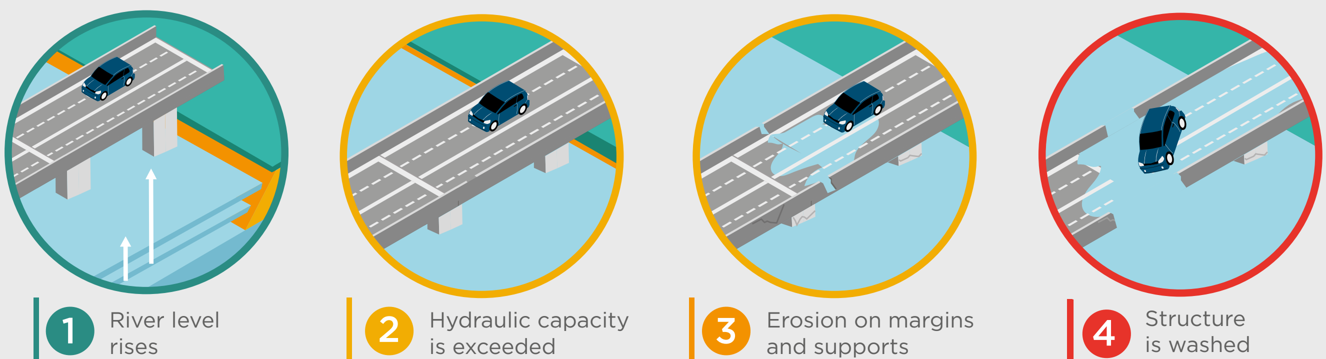
One of the most important lessons learned that led to the development of this Methodology was the need for projects to undergo a qualitative analysis before assessing the need for a more complex quantitative analysis. The qualitative risk assessment may: (i) lead to a disaster and climate change risk management plan directly, if the analysis concludes that it sufficiently evaluated all risks, that none of them pose a threat to the project's viability and, based on the results, it is possible to propose measures that lead to a tolerable risk level, or (ii) serve as a basis for establishing the scope of a subsequent quantitative assessment, when necessary. In other words, this qualitative step is another filter to identify the aspects that require a quantitative assessment, if any. The Risk Narrative developed in Step 3 should feed this complete qualitative analysis, initiating the analysis.

Because of time constraints, lack of data, or aspects that are not fully quantifiable, oftentimes a qualitative assessment makes the most sense, either as a stand-alone assessment or as a steppingstone to a quantitative assessment. There are many approaches, and it is advisable to check which ones are most commonly used in specific fields of study. The Methodology describes three of them: a risk matrix approach, a failure-modes analysis approach, and qualitative analysis using surveys/interviews with a panel/group of experts using techniques such as the Delphi method (Box 5.2). Moreover, specific methods or techniques may be used for this.

Various examples of these tools can be found in the literature or in other institutions, such as the PIEVC Engineering Protocol by Engineers Canada[16] (Engineers Canada, 2016), which includes an important qualitative and workshop component. For a small, moderate-risk project with a tight budget and timeline, any of these qualitative approaches might make more sense than a complex quantitative analysis.

Box 5.2. Types of Qualitative Disaster and Climate Change Risk Assessments

A qualitative assessment can be done through a workshop (Failure-Mode workshop) where disaster risk management and climate change experts work with technical personnel from the design/construction firms and the operation's executing agency to discuss and gauge all possible risks, contributing factors, potential consequences and intervention measures. Other qualitative techniques include formally using the Delphi method for consulting expert opinion (a consensus-building method of performing group surveys or interviews with a select panel of experts) (Hallowell and Gambatese, 2010; Garson, 2012) or using risk matrices that rate risks based on qualitative estimations of frequency and magnitude of impacts. In all cases, local professionals and technicians must be involved to make sure local knowledge is mined. The following figures show an example of a schematic mode of failure for a road identified through a failure-mode workshop.



16 https://pievc.ca/. See, for example, case study, available at https://pievc.ca/sites/default/files/quesnell_bridge_city_of_edmonton_refurbishment_alberta_final_report.pdf.

What should a qualitative risk analysis for an infrastructure project include?[17]

- **Information on the project**[18]**:** Identification of the project: it is best to have some preliminary design information.
    - What is the scope of the operation: new design/construction, modernization/improvement, planning, or others?
    - What is the expected useful life of the different components of the operation?
    - How many people will the project serve?
- **Natural hazards and exposure:** Identify the natural hazards that can potentially affect the project's direct and indirect area of influence.
    - Specific characterization of the hazards that can affect the infrastructures throughout its life cycle.
    - Evaluate current degree of exposure in terms of population, economic and cultural assets of the location, and area of direct and indirect influence of the infrastructures.
- **Project vulnerability:** Identify the characteristics of a project that make it more/or less vulnerable to natural hazards, including climate change. Through an analysis such as Failure Modes: Identification and analysis of failure modes of the project in the face of natural hazards during its life cycle, integrating the climate change variable and recommendations for each failure mode identified. Determine how critical it can be for a project to fail. If any of the components of the project fail, is there a potential to cause loss of life? Are there systems or redundant infrastructure that could be used if some component of the project fails?
- **Plausible impacts:** As far as possible, qualitative evaluation of the incremental exposure (in relation to the existing one) in terms of population and the economic and cultural goods due to the implementation and/or operation of the project. Identify, to the extent possible, the plausible impacts in social and economic terms that are strictly attributable to the existence of the project, and the environmental impacts that might exacerbate the risk (e.g., impact to mangroves in a port zone, hazardous materials in case of an earthquake, etc.).
- **Technical visit:** Field recognition of the project site with relevant stakeholders to visually identify and gauge the current situation of both natural hazards and existing infrastructure, if any. A detailed *aide memoire* that includes a comprehensive photographic record should be created.
- **Workshop:** Undertake a workshop with relevant stakeholders to analyze possible failure modes and identify possible risk reduction measures and complementary works, analyze risk exacerbation or transfer to third parties, identify if further studies are needed.
- **Aid to decision making:** Conclusion on whether the level of qualitative detail is sufficient to justify the project's feasibility.
- **Plan:** Development of a disaster risk management plan for all failure modes that will not need to be analyzed in the quantitative phase (short-, medium-, and long-term measures).

5.2.2.1 Risk matrices

A risk matrix consists of a matrix that defines categories of frequency and severity (or consequences) of risk, each one on one axis. The first step to apply this approach is defining

17 Disaster Risk Assessment Online Course, IDB, forthcoming 2019. Source: *Ipresas*.

18 Note that some of this information should already be available from Step 3.

or constructing the risk matrix, and this entails establishing categories for frequency and severity. Risk matrices can be built using qualitative or semi-quantitative categories or thresholds.

To define categories for frequency, define the number of categories needed (e.g., four categories defining very low, low, moderate, and high frequency) and optionally define what thresholds differentiate each category (e.g., very low: less than once every 1,000 years, low: from once in 100 years to once in 1,000 years, moderate: from once in 10 years to once in 100 years, and high: more than once in 10 years). To define categories for severity, consider which types of impacts are more appropriate for the specific project under study, such as damage to property, economic interruptions, environmental impacts, fatalities, and/or injuries, and optionally define specific thresholds to differentiate each category (FEMA, 1997).

The steps to be followed to use a risk matrix are (FEMA, 1997):

1. Identify and characterize the hazards of study, including severity and interrelations with other hazards.

2. Estimate the risk of each identified hazard based on the relative degree of risk obtained from the risk matrix and rank order these risks.

3. Assess acceptability to determine if the identified risk levels can be tolerated or not.

4. Simulate and test on the matrix possible risk mitigation measures that would control the risk to acceptable levels.

5. Periodically monitor and review risks using the matrix.

Usually, different quadrants or areas within the matrix are given a qualitative classification that determines what types of actions are needed and permits the ranking or comparison of different risks. Hence, the upper-right hand corner of the matrix would require immediate action and the highest priority for mitigation and contingency planning, whereas the lower-left hand corner of the matrix would only merit advisory risk mitigation measures (FEMA, 1997).

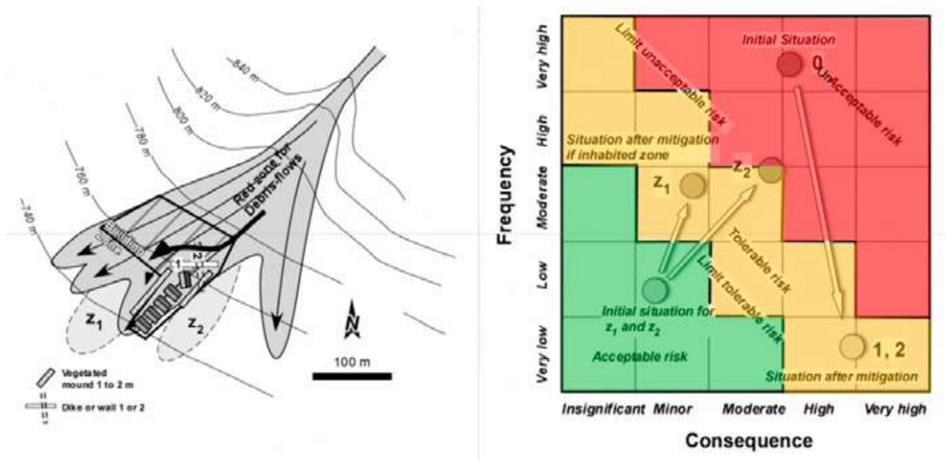
As noted by the CHARIM (Caribbean Handbook on Risk Information Management) project (Haimes, 2008; van Westen, n.d.), this method allows more flexibility and incorporation of expert opinion. It offers a way to visualize the effects and consequences of risk reduction measures. It is also a good communication tool because it makes it easier for non-experts to understand a risk assessment. The results will depend heavily on the experts involved in the process of creating the matrix. Therefore, selecting the group that will inform the process, including the identification of the hazard scenarios and the ranking characterized by frequency (probability) and impact classes and their corresponding limits is very important. See Figures 5.1 and 5.2 for some examples.

Figure 5.5-1. Example of the Risk Matrix Approach

		Impact			
		None	Small	Moderate	High
Frequency	Very High		High	Very High	Very High
	High		Moderate	High	Very High
	Moderate		Low	Moderate	High
	Low		Low	Low	Moderate
	None	No Risk			

Source: C.J. van Westen in The Caribbean Handbook on Risk Information Management. http://www.charim.net/methodology/55

Figure 5.5-2 Example of Potential Building Area in a High Hazard Area and Illustration of the Proposed Solutions



Source: CHARM http://www.charim.net/methodology/55
Note: The risk matrix is used to represent the degree of risk (Jaboyedoff et al., 2014).

5.2.2.2 Panel of experts (for example, using the Delphi method)

The Delphi technique allows researchers to obtain highly reliable data from certified experts using strategically designed surveys. It provides an interactive, systematic, and structured approach to obtain the judgment of a panel of experts, particularly in this case, on opinions on identification, probability and consequence estimation, and risk evaluation. It is rated as medium (compared to other techniques) regarding resources and capabilities needed, nature and degree of uncertainty, and complexity. It can be used to weigh hazard and vulnerability indicators. It makes it possible to perform a multi-risk assessment in the event of incomplete or incomparable data sets. As this is a relatively well-known approach, resources for further reading are provided. This method can be integrated into a workshop and site visit format, in line with the discussion on Failure Mode Analysis. This technique is used by several agencies including the United Nations Office for Disaster Risk Reduction (UNDRR, formerly known as UNISDR).

5.2.2.3 Failure Modes Analysis

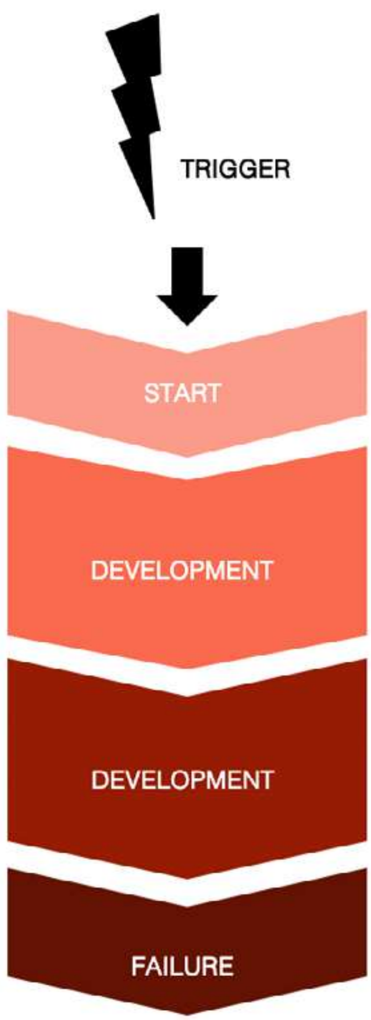
Failure Modes Analysis is an analysis by local stakeholders and technical experts to identify failures, causes and solutions and developing a plan consisting of structural/non-structural measures to reduce risk. Generally, this analysis is carried out in a workshop organized for this purpose.

A qualitative risk analysis of failure modes aims to review the various aspects related to the safety of an infrastructure in an integrated way, identify the potential failure modes that could occur, and make recommendations to improve safety management, such as actions aimed at reducing risk and increasing knowledge about the system. A failure mode analysis is an example of a qualitative risk analysis that is based on the identification of failure modes for the relevant infrastructure. It includes the set of events or mechanisms that may lead to the failure of the infrastructure, related to either **structural** (collapse), **operational, or service** (interruption of its function, e.g., cutting a road) aspects.

How is a failure mode defined?

A failure mode is defined as the series of events that can lead to inadequate functioning of the infrastructure, its risk management system, or one or several of its parts or components. This series of events is associated with a certain hazard scenario. It has a logical sequence, consisting of an initial triggering event (e.g., a flood or an earthquake) and a series of development or propagation events, and it culminates in the failure or malfunction of the infrastructure (e.g., a service failure) (Figure 5.3). The potential failure modes that can be identified for the same infrastructure must collect all those events or combinations thereof that may give rise to both structural and service failures.

Figure 5.3. General Structure of a Failure Mode



What factors should be identified to analyze their possibility of occurrence?

Factors that should be identified include technical and organizational factors, among others, that contribute to or hinder the occurrence of the triggering event and the progression of the mechanisms that ultimately give rise to the failure. Special attention should be given to factors related to the **operation and maintenance** of the infrastructure, the **design**, and the **concurrence of other events** that may enhance the development of the failure.

The participation of **technical experts from different disciplines** (e.g., structural engineers, hydraulic engineers, mechanical engineers, geotechnical engineers) in the identification of failure modes allows a more comprehensive vision of infrastructure safety and an understanding the interrelationships involved. However, care should be taken not to make it too large (in number of participants) to control. It is important to keep the discussion focused.

The analysis should identify potential failure modes and classify them to identify which ones require more attention and analysis.

What is the process?

Typically, a disaster risk specialist is needed to conduct this complete qualitative analysis and to lead and guide the process involving all stakeholders. This may require additional expertise and more profiles than those developed by the project and engineering teams. Thus, the team needs to decide if there is a need to procure consultancy services for this purpose.

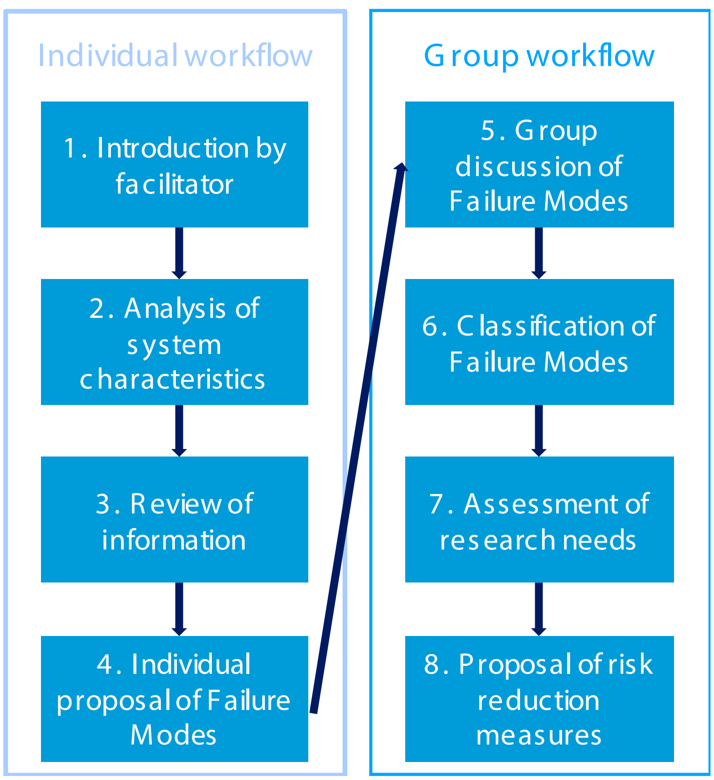
The failure modes analysis starts begins with the collection and analysis of project information from secondary and primary sources, including a technical visit to the project site. The visit, conducted by the disaster risk experts, the project team, and the project engineers or designers, is critical to the process as it provides everyone with a common understanding of the baseline conditions and an opportunity to discuss the project concept and proposal, including technical details. The field visit must precede the workshop to gather first-hand information of the current state of the project and to familiarize the team with the direct and the indirect project area. It possible that some failure modes can already be identified during the site visit, as well as particular conditions of the project that may hint at certain hazard or infrastructure aspects that should be analyzed in more depth. After the site visit, a workshop should be carried out to develop possible failure modes.

The process followed in the workshop to identify failure modes is shown in Figure 5.4. As can be seen, after the review of system information and the technical visit, each member of the team that is carrying out this activity—ideally between 5 and 15 people with different degrees of involvement in the project and a wide spectrum of expertise—identifies failure modes. The project information collected and discussed at the beginning should consist of preliminary or pre-feasibility designs so that minimum technical specifications, scope, beneficiaries, general dimensions, general layout, alternatives, and location are known. This complete qualitative risk assessment aims to inform and influence the final designs. This is why the preliminary design stage is the optimal stage in the project development in which to conduct it. In this phase, each participant makes an individual proposal about possible failure modes that could emerge in the system.

Individual proposals for failure modes should be shared within the team to eliminate redundancies and obtain the group's aggregated list of failure modes that have ideally been established by consensus. In addition, for each failure mode identified, the group must list the factors that both propitiate and hinder its occurrence. When proposing and analyzing failure modes, it is important to evaluate the exposure, vulnerability, and risk of people or assets outside the project itself (i.e., third parties) who may be impacted by the project's failure. Finally, from this identification of failure modes, the participants will be able to propose improvements to the infrastructure and/or to the exposed third parties (e.g., implementation of risk reduction measures in downstream towns).

There are many examples of failure modes and of procedures for identifying failure modes in the technical literature, but results are specific to each type of infrastructure. Some examples that were conducted for IDB projects are the following: Quality Control of the Risk Analysis for Flood Control Works in the Choluteca River (Technical Cooperation RG-X1226), and the Transport and Departmental Connectivity in Haiti (HA-L1104[19]). The formal process of identification of failure modes is an essential step that precedes the quantitative analysis.

Figure 5.4. Process to Identify Failure Modes in the Workshop



19 A summary report can be found at https://www.iadb.org/Document.cfm?id=EZSHARE-69529135-44

Two or three days before the workshop, it is helpful to send invitees the following information: (i) project overview, (ii) hazards of concern identified in the previous steps, (iii) project design documents gathered in Step 3, and (iv) an agenda. An example of key elements of the agenda can be found in Box 5.3. This agenda was developed to support a six-hour workshop and may be adapted to the project's needs.

Among the issues to be discussed during the workshop include the following: potential failure mode, description of failure mode, graphical representation of failure mode, factors that would make the failure more likely (including consideration of climate change), and factors that would make the failure less likely. Future conditions and inter-dependencies should be integrated into the conversation. How will this area change in the future? What other stressors should be considered? How do the failure modes relate to one another?

Box 5.3. Key Aspects of the Workshop Agenda

Project overview: to be presented by the IDB project team together with the Executing Agency.

Current design, data, and project availability (60 min.): to be presented by the design/construction firm(s). This session is aimed at understanding and discussing the design details and technical topics.

Disaster risk overview (30 min.): to be presented by the person/entity/firm in charge of the qualitative risk analysis to discuss the findings from Steps 1, 2 and 3, coarse scale data, and the data/studies that were collected.

Individual failure modes work (20 min.).

Group discussion on individual work (40 min.).

Classification of failure modes (60 min.).

Group discussion of proposal of risk reduction measures (60 min.).

Who should attend the workshop?

The working group that performs the analysis should include experts in **natural hazards** and the **infrastructure** under analysis. Stakeholders included in the qualitative risk analysis process must be: (i) multidisciplinary: they should have expertise in different areas and fields of knowledge (technical, financial, organizational, social, environmental, management, etc.); (ii) knowledgeable about the system, that is, the infrastructure and its environment, operation, and maintenance; (iii) experienced and qualified according to the needs of the analysis: they should be experts in the hazards under analysis, the type of infrastructure, and the phase of the project life cycle. A representative of the project team should also participate in, and could eventually facilitate, the workshop. If a disaster risk assessment has been or is to be carried out, the consultant or firm responsible for it and the firm designing the infrastructure should also be present. It is important to ensure that the workshop is small enough to allow everyone to participate but diverse enough so that no key skillset or point of view is missing.

5.2.3.Analyzing the results of the Qualitative Disaster and Climate Change Risk Assessment and Developing a Disaster Risk Management Plan

This task involves reviewing the results of the failure modes analysis and determining whether it addresses the risks sufficiently or if Step 5 is required for the whole project or any of its components. Therefore, in this stage, the project team must decide if: (i) if the risks can be mitigated through the mitigation measures proposed by the qualitative analysis and implemented without a detailed risk assessment, or (ii) if a more detailed risk assessment is needed.

For those projects that do not need to move to Step 5, the qualitative analysis of Step 4 must lead directly to a DRMP. Similarly, even for projects that do need to move to Step 5, sometimes the results from Step 4 may already provide some risk mitigation measures that must be included in a DRMP, which may be completed subsequently the results from Step 5. The DRMP should include a combination of structural and non-structural measures, as well as relevant recommendations to address environmental issues (e.g., mangroves providing ecosystem services both in terms of environmental benefits and flood protection in a port zone, or potential issues with spills of hazardous materials as a potential derived impact of an earthquake), even if these are qualitative. For some examples of risk mitigation measures, see Appendix G.

It is important to document the justification for each measure selected in terms of its effectiveness in achieving risk reduction objectives. Justification should include a qualitative account of the significance of the risk reduction benefit and discussion of any residual risk. A general outline of a DRMP derived from a qualitative assessment is shown next.

1. Qualitative Disaster and Climate Change Risk Assessment Summary
    a. Estimated Qualitative Risk (by Priority Hazard)
        i. Baseline Risk without the Project (especially for surrounding communities)
        ii. Risk with the Project (risk to infrastructure and operations, and creation or exacerbation of risk to surrounding environment and communities)
2. Identification and Prioritization of Risk Management and Risk Reduction Options
3. Management Plan
    a. Measures Targeted at Project Design, Construction and Operation
        i. For the project
        ii. For third parties (surrounding communities)

5.2.4 Links and Consistency between the Complete Qualitative Risk Assessment and further Quantitative Risk Assessments

Even if a complete qualitative risk assessment constitutes a final product with an associated DRMP, in the case that the project's technical and economic viability cannot be guaranteed with this assessment alone, this step will drive the need to conduct a quantitative assessment for all or some specific failure modes. This also means that the DRMP obtained from Step 4 will need to be complemented with the results and findings of the quantitative assessment (Step 5). This has particular relevance given that:

- The level of analysis required for the subsequent quantitative assessment (if needed) is associated with specific failure modes or aspects of the project and not to the entire project. This means that failure modes associated with a qualitative analysis may coexist with other failure modes that require a quantitative analysis of lesser or greater complexity.
- The link between Steps 4 and 5 should always be maintained even if these steps are part of different Phases (Phase II and Phase III) in the Methodology. This means that the Terms of Reference for a quantitative assessment (Step 5) should necessarily include a review of the qualitative analysis (Step 4) so that: (i) the link between the quantitative analysis and the specific project characteristics in terms of hazard, vulnerability, and criticality is guaranteed; and (ii) the level of effort required is proportional to the level of analysis needed for each failure mode. See Appendix I for sample templates of Terms of Reference.

For those failure modes that require a quantitative assessment, the depth of this assessment should be proportional to: (i) the availability of data, (ii) the impact of the uncertainties associated with climate change and population dynamics, (iii) the existence of risk tolerability and/or acceptability criteria for specific sectors, and (iv) the potential dependence on the technical and economic viability of the entire project. This results in a wide spectrum of cases ranging from relatively simple assessments to very complex ones, as is reflected on the sample template of Terms of Reference presented in Appendix I.

By establishing a mechanism to effectively link the qualitative (associated with the engineering, geographic, and social reality of the project through the identification of failure modes) and quantitative (associated with mathematical and statistical modeling) analyses, the goal is to avoid the following:

- A dominance of hazard assessments based solely on the project's location.

- A decoupling of the project's specific engineering and characteristics and the risk assessments, which may hinder the creation of added value.

- A lack of pondering and planning of the modeling and simulation efforts due to the lack of a conceptual framework that defines the strategy and identifies opportunities for calculations in terms of the decisions to be made.

At this point it is worth recalling the main concept of the Disaster Risk Management Policy, as it provides the core principle on the potential technical and economic viability of a project. It states the following:

"Bank-financed public and private sector projects will include the necessary measures to reduce disaster risk to acceptable levels as determined by the Bank on the basis of generally accepted standards and practices. The Bank will not finance projects that, according to its analysis, would increase the threat of loss of human life, significant human injuries, severe economic disruption or significant property damage related to natural hazards."

Hence, the level of analysis should be oriented toward being sufficient to justify that the last condition is met. Moreover, when assessing the risk to nearby communities, both the incremental risk to these communities and any additional impacts generated by the project's implementation should also be identified and considered separately, as presented in the sample template of Terms of Reference in Appendix I.

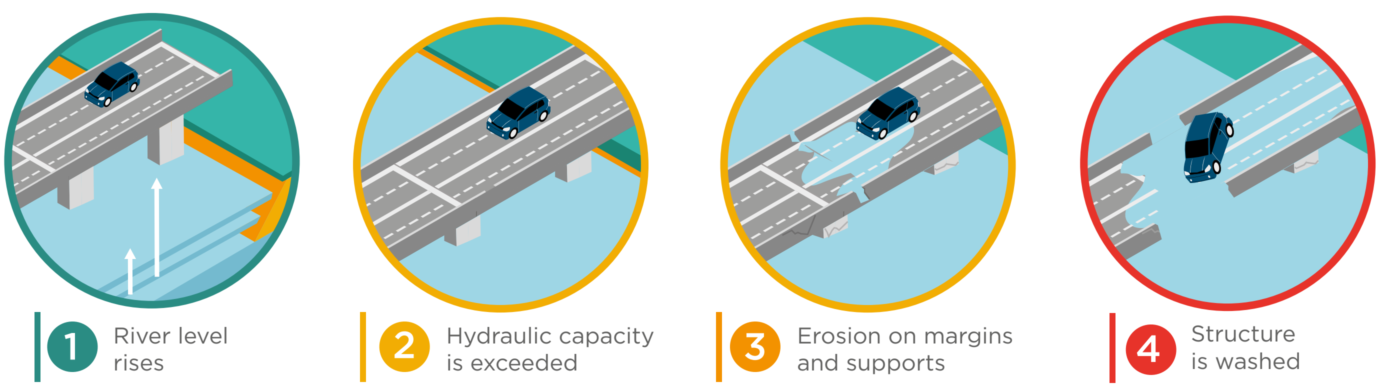
Consequently, there may be cases where the implementation of a project generates new or additional impacts on third parties that would not occur without the project, but that in terms of risk would decrease the risk to these third parties. In these cases, the project's viability would not be compromised, but this is independent of the fact that these impacts should be identified and evaluated as well.

Two examples are shown next. The first is an example of a summary profile of a specific failure mode which describes the failure mode, includes a diagram illustrating it, and analyzes the possible factors that either exacerbate or reduce the risk associated with it. The second shows a case where a Failure Modes Analysis was conducted, and it was determined that it was necessary to continue to a quantitative assessment (Step 5) for a few of the identified failure modes. This example is taken from Escuder-Bueno et al. (2016).

5.2.5 Example 1: Failure-Mode example for a road project

Figure 5.5. Example of a Sheet Used in a Failure Mode Workshop

Failure mode title
Failure mode description
During an extreme hydrometeorological event, an increase in the river discharge may be large enough to surpass the capacity of the transversal drainage structures (including culverts and bridges) along the road. Water starts to accumulate upstream of the structure until it overflows the riverbanks and the structure itself. At this point, traffic across the structures is interrupted. Sustained or increased conditions of overflow may increase flow velocity and turbulence, generating increased dynamic loads on the structure and erosion of its supports. Eventually, and in the worst-case scenario, the flow may completely wash out the structure.
Graphical representation



Factors that attenuate the risk	Factors that increase the risk
• An alternative alignment of specific road sections may largely avoid problematic areas where the road runs parallel and very close to water bodies. • This failure mode only occurs in a few specific sites (it is not widespread or generalized for the entire road); this means that the damage to the road would be partial and in no case would mean the total loss of function of the road or cause major loss of life.	• Past events have completely washed out culverts and bridges, indicating that (possibly) existing structures do not have adequate capacity. • In many cases these structures are the only option to cross rivers and, if they were to fail, some communities may become isolated (no redundancy). • In general, foundations appear to be superficial. • Climate change may increase the intensity of precipitation related to hurricanes and the discharge values also due to changes in land use and deforestation, resulting in higher flooding risk.

5.2.6 Example 2: Complete Qualitative Risk Assessment leading to a Quantitative risk Assessment (Escuder-Bueno et al., 2016)

In this example, a system of dams for hydroelectric production within a river basin is analyzed for disaster risk. The system of dams produces around 4-5 TWh of power annually, representing a major contribution to the country's power supply, and is comprised of three different reservoirs with the following characteristics (Escuder-bueno et al., 2016):

- **Fierza Reservoir:** created by the Fierza dam, which is a rock-fill embankment dam with a clay core built from 1971 to 1978 with a fairly symmetric section, a total height of 167m and total storage of 2700 hm³.

- **Komani Reservoir:** created by the Komani dam, which is a concrete faced rock-fill embankment built from 1980 to 1985 with a fairly symmetric section, a total height of 115.5m and total storage of 500 hm³.

- **Vau I Dejes Reservoir:** created by three separate embankments with a total storage of 680 hm3. The Qyrsaqi Dam is a zoned rock-fill embankment dam with clay core and an adjacent concrete gravity dam with a height of 54 m and total length of 548 m. The Zadeja dam is a rock-fill embankment dam with clay core and a height of 59.5 m. The Ragam dam is a rock-fill embankment dam with clay core and a height of 21 m.

First, the existing information was reviewed and analyzed, and a site inspection was conducted to ensure a common understanding of the project. Then, a Failure Modes Workshop was conducted where various failure modes were identified in a group session. In total, 11 failure modes were identified (Figure 56). These were divided in two groups: failure driving by internal erosion processes and failure driven by overtopping (Figure 57). Each failure mode was analyzed including the factors that accentuate or attenuate the risk associated with each.

Figure 5.5 Summary of identified failure modes for the three reservoirs in the Drin River.

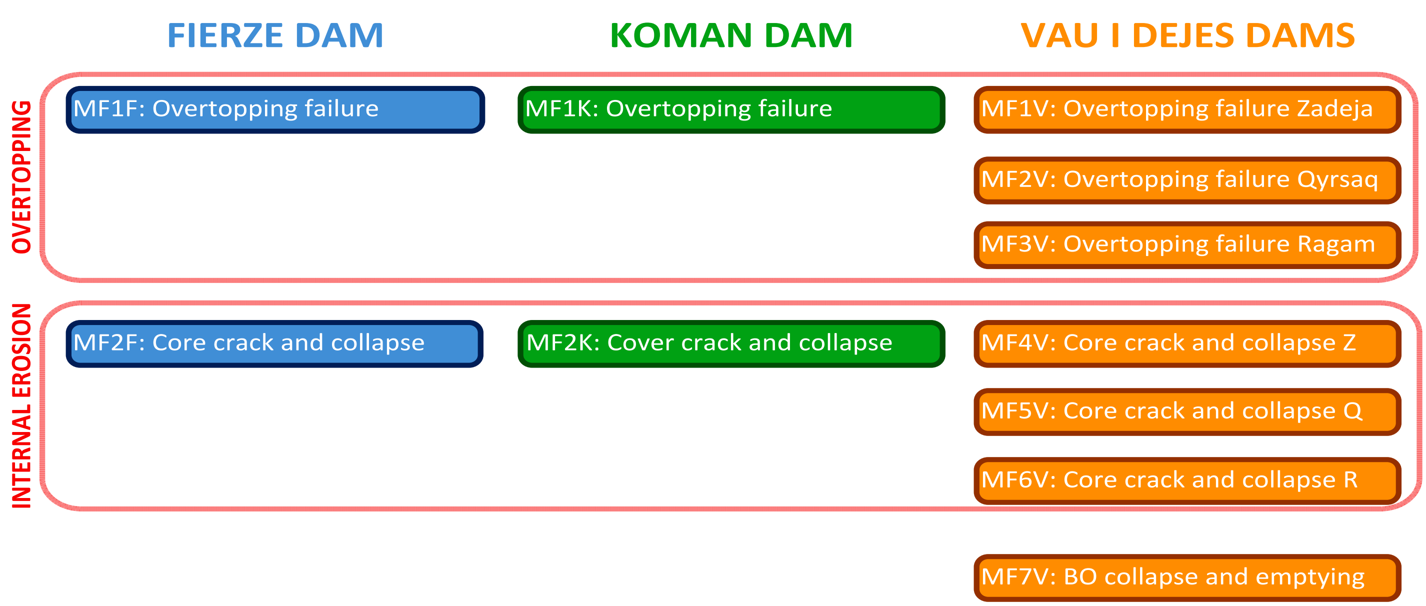
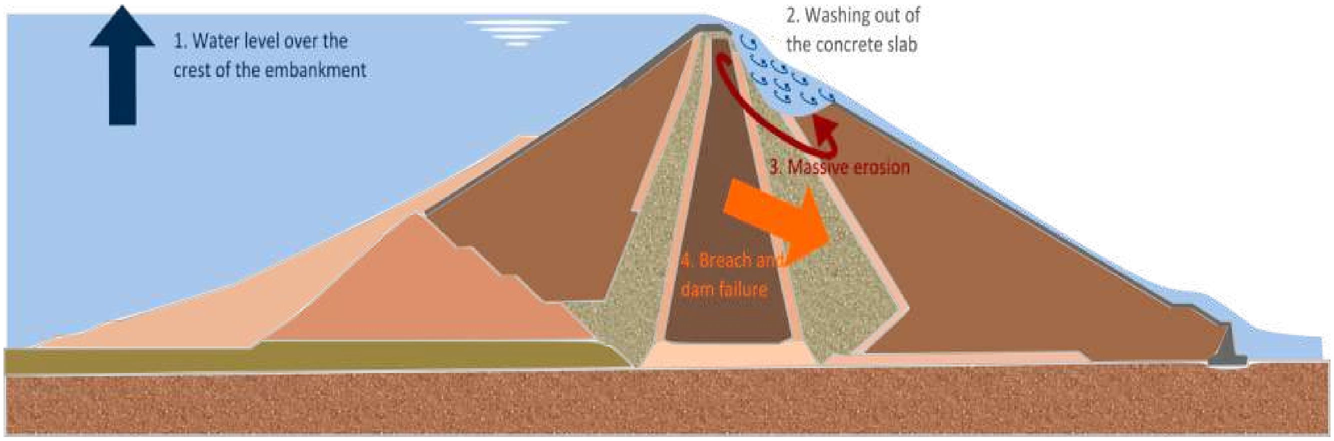


Figure 56. Overtopping failure mode in Fierze embankment.

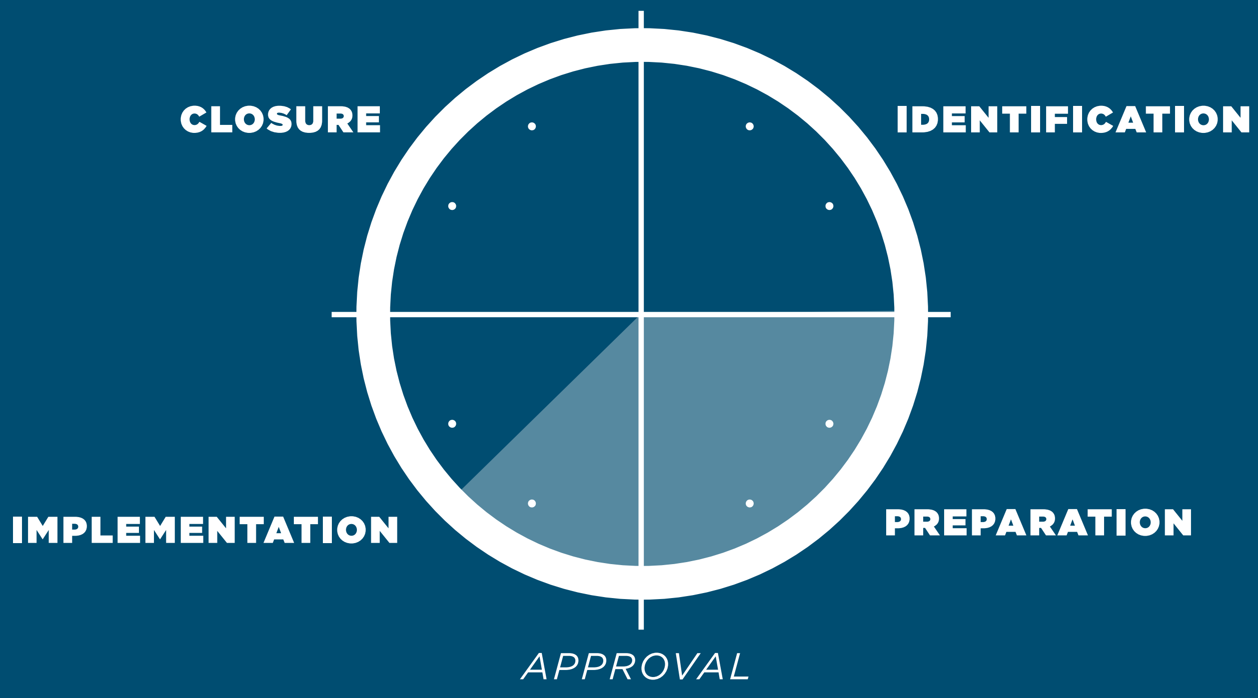


This Complete Qualitative Risk Assessment formed the basis to identify potential disaster risk mitigation measures. The first group of failure modes, related to internal erosion, were found to be strongly driven by uncertainty, so risk management efforts should focus on improving surveillance and monitoring first to reduce the uncertainties before evolving towards a quantitative phase.

For overtopping failure modes, some needs were also identified to reduce uncertainties, and it was determined that a quantitative risk assessment was needed. The quantitative risk model of the system of dams is explained in Step 5, where the effect of risk reduction measures was evaluated.

6. PHASE III: Quantitative Assessment

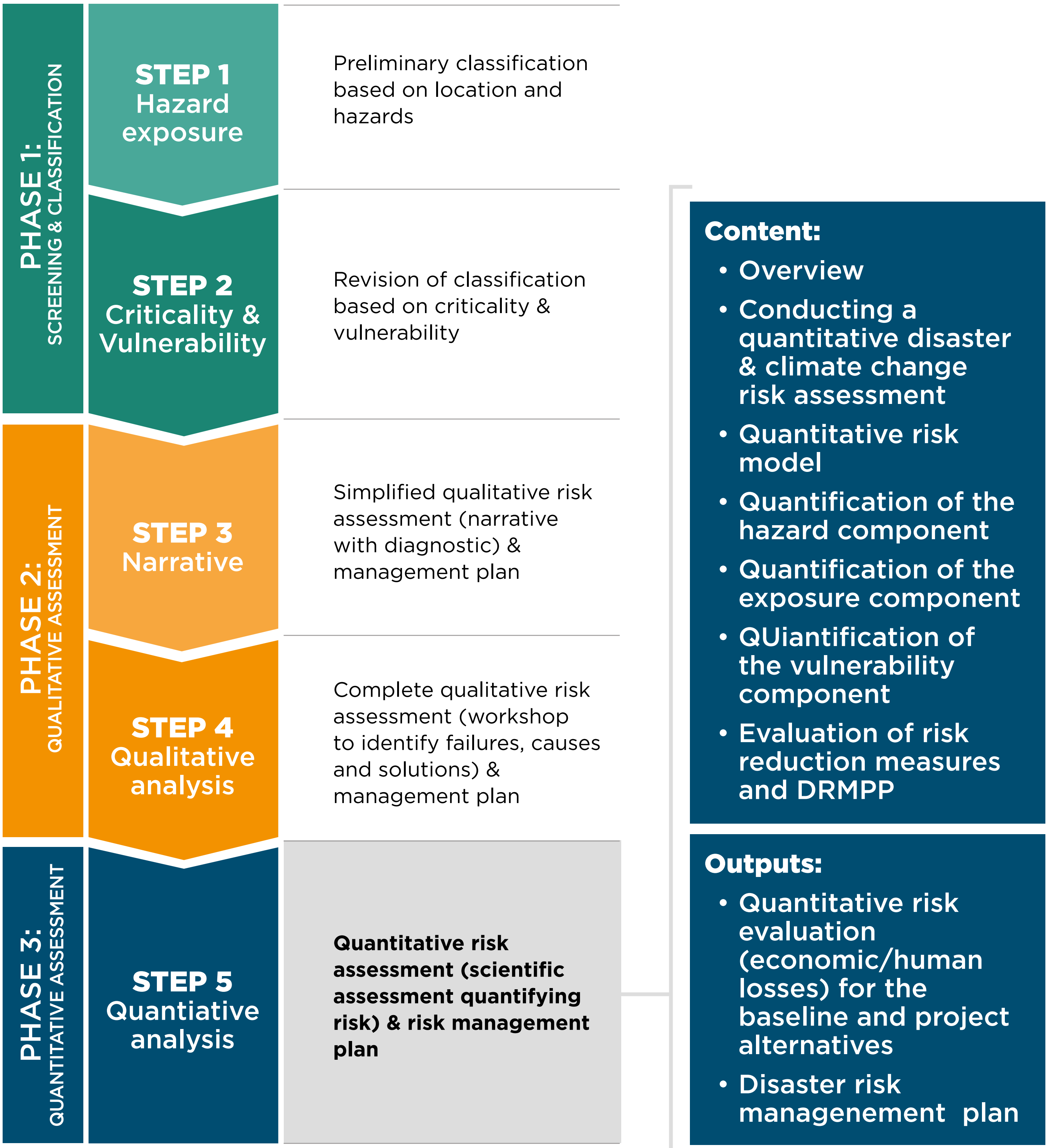
This phase should be conducted once there is more definition on the project. The first step should occur prior to approval (during the preparation stage), but the second step can occur during the early stages of implementation when the necessary project details are only known at a later point.



6. Phase III – Quantitative assessment

6.1. Step 5 – Quantitative Risk Assessment and Risk Management Plan

Figure 6.1. Step 5



6.1.1 Overview

The fifth step in the Methodology is to conduct a quantitative disaster and climate change risk assessment for those high- or moderate-risk projects that require it or that would benefit from one. To do so, a variety of methods or approaches are provided. This step will help answer the question: What are the expected economic and human losses both to the project as a result of a natural hazard and to third parties (nearby communities) as a result of the project possibly exacerbating the disaster risk conditions?

Consistent with what was discussed in Section 5.2.4 in Step 4 and regardless of the level of complexity of the quantitative analysis, the following basic attributes should be part of any quantitative assessment:

- The project and its infrastructures are described with a reasonable level of detail: infrastructure typology, general dimensions, foreseen constructive processes/procedures and future characteristics of operation.

- All natural hazards that may potentially affect the project's area of influence are identified.

- Specific natural hazards that may affect the project during its life cycle are characterized. The current degree of exposure is studied in terms of population, economic and cultural assets of the project's location, and area of influence.

- The incremental exposure with respect to the current exposure is studied in terms of the changes in population, economic and cultural assets by the project's implementation and operation.

- A complete qualitative risk assessment (e.g., through a Failure Modes Analysis) is conducted for both natural and intrinsic (to the type of infrastructure) hazards for the project's life cycle.

- The current risk is estimated from the characterized hazards and current exposure.

- The incremental risk attributable to the implementation of the project is estimated with respect to the current risk.

- The impacts of climate change and other relevant uncertainties are considered in the risk estimation (current and incremental).

- An evaluation of tolerability and/or acceptability of the risk attributable to the project is conducted.

- A series of risk management measures are proposed according to the tolerable and/or acceptable risk attributable to the project.

- Recommendations that improve the state of the art of the customary disaster risk management procedures for the type of project are established.

- An economic analysis of the proposed risk management measures is conducted.

- The technical and economic feasibility of the project is determined using the set of proposed risk management measures.

6.1.2 Conducting a quantitative disaster and climate change risk assessment

When conducting a quantitative risk assessment at the project level, the following principles must be taken into account:

- Risk should be assessed both without and with the effects of climate change on hydrometeorological hazards. This results in two configurations of the risk model.

- Risk should be assessed for both the project and the nearby communities (including the possibility of exacerbation or creation of new disaster risks due to the construction and operation of the project). This results in two perspectives in the risk assessment.

- Risk should be assessed for both the baseline (i.e., pre-project) conditions and the resulting conditions of introducing the proposed project, ensuring no additional increase in risk to the community or environment after the project has been added. This results in two additional configurations of the risk model.

- Risk should be assessed for any proposed project design alternatives and/or for any risk reduction measures.

In addition, it is important to highlight that in assessing the risk to the surrounding communities, special care should be taken to identify (i) the incremental risk to these communities before and after project implementation and (ii) any additional consequences (impacts) on these communities as a result of implementation. This should be done bearing in mind the difference between risk and impacts, where risk refers to the end result of combining the magnitude of a consequence with its frequency of occurrence, whereas impact refers to the individual and frequency-independent consequences. Hence, there may be cases where the implementation of a project reduces the risk, but generates new or additional consequences on its surroundings that would not have occurred without the project (e.g., building a dam can reduce the flooding risk to a community downstream, but it now creates the new possibility of that community suffering destructive and fatal torrential flooding if the dam fails, even if the probability is very low). Consequently, incremental risk identifies how the risk to the surroundings (enveloping both recurrent-small and rare-large events) changes with respect to the situation without the operation. Care should be taken to ensure that the new investment does not exacerbate the risk to its surroundings. In addition, the newly generated impacts should also be identified, assessed, and included in the disaster risk management plan.

To build the quantitative risk model, four tasks should be completed:

Task 1: Identify a method or approach to quantitatively assess risk that is appropriate for the project, the level of detail needed, and the amount of data available.

Task 2: Conduct a baseline risk assessment for both the project and the communities located in the influence area.

Task 3: Conduct a risk assessment evaluating project design alternatives, risk reduction measures, and final design.

Task 4: Build a disaster and climate change management plan, including a compilation of all risk reduction measures finally selected after the analysis of alternatives conducted in the previous task, including the measures to be considered during the construction and operation phases.

Following these principles and tasks, a quantitative risk assessment should have the following structure (this structure may be used in the Terms of Reference for a quantitative assessment):

A. **Task 1: Identify an approach to quantitatively risk assessment** that is appropriate for the project and adequate for the level of detail needed and the amount of data available.

B. **Task 2. Build a risk model and conducting a baseline risk assessment** (current conditions, pre-interventions) for the project itself and the communities located in the influence area.

   For hydrometeorological hazards: for each analysis, two configurations of the risk model should be developed: one that does not consider climate change and one that does.

   The risk model contains the following components (see Disaster and Climate Change Risk Overview above):

a. **Hazard evaluation:** evaluate the hazard(s) identified as a critical part of the qualitative risk assessment in terms of spatial extent, intensity, and frequency. ***For hydrometeorological hazards:*** Two hazard conditions should be considered—one that does not consider climate change and one that does.

b. **Exposure evaluation:** assemble a geodatabase of all the physical assets (e.g., infrastructure, buildings, crops, etc.) and social assets (population) that are part of (i) the project itself, if something already exists and/or it comprises multiple assets that are spatially distributed; and (ii) the surrounding area of influence (i.e., nearby communities or settlements).

c. **Vulnerability evaluation**: evaluate the vulnerability conditions of (i) the project itself (if something already exists) and (ii) nearby assets and population.

d. **Risk evaluation:** evaluate the resulting risk from the combination of hazard, exposure and vulnerability, evaluated above. ***For hydrometeorological hazards:*** this calculation is done twice, using the hazard model without considering climate change and with climate change.

The results of this evaluation are expressed in terms of estimated economic losses and losses to human life, with and without climate change effects. Hazard and risk maps can also be developed.

C. Task 3. Conducting a Risk Assessment evaluating project design alternatives, risk reduction measures, and final design.

Based on the risk model built in numeral B (Task 2), introduce the proposed project, together with risk reduction/mitigation/intervention measures or design alternatives, and conduct a second Risk Assessment using the same methods and conditions. This activity consists of the following specific actions:

a. **Introduce the project and risk reduction measures into the risk model:** introduce the proposed project, including alternatives, into the model using the available designs. This may result in a modification of the modules. The introduction of infrastructure may modify the hazard (usually this is the case with flooding hazards where infrastructure can become a physical barrier), the vulnerability (including the vulnerability of the elements of the project and the modified vulnerability if the project entails rehabilitation/upgrade of an existing infrastructure), or the exposure (the additional number of people or value of new assets that are now exposed to hazards as a result of the project). It is recommended that at least pre-feasibility designs be available to conduct the risk assessment—anything less will result in very generic risk assessments with little value added—but designs should not be completely finalized so that the results from the Risk Assessment can influence the design in an iterative process. As part of the iterative process, risk reduction measures will be considered, including structural (e.g., physical construction or engineering techniques or technology) and/or non-structural (e.g., policies, laws, contingency planning, early warning systems, training or education). The aim of these measures is to reduce the risk associated with the most critical modes of failure identified in the qualitative risk assessment. These measures include changing the designs or providing guidelines and strategies to reduce and manage the risk of the project and to its influence area. When identifying the measures, approaches to reduce the uncertainty of the action under climate change scenarios, such as low-regret measures and flexible design, should be considered.

b. **Run a second risk assessment:** different risk models will be built for each critical failure mode identified in Step 4, considering the modification of the risk generated by the different measures, conceptualized at least at pre-feasibility level. The risk assessment may be carried out choosing from a variety of methodologies ranging from simplified to highly complex. In many cases a project-specific risk assessment could be carried out using simplified methodologies (e.g., deterministic modeling), considering that the objective of the modelling is to identify the measures that reduce risk to a tolerable level (see tolerability standards) and which make the project viable from a socioeconomic perspective. In this task, communication between the project's design process and the risk assessment process is key.

The results of this new evaluation are expressed in terms of the estimated economic and human losses. The results of the final risk assessment will be used to estimate the socio-economic viability of the project as well as the incremental risk and its tolerability. To estimate the incremental risk, the results of the final risk assessment should be compared with the results from Task 2, analyzing the differences in losses between the baseline and the post-operation implementation conditions and comparing the results with the tolerability standard. Hazard and risk maps can also be developed, both to evaluate the economic viability of the project and compare it to the maps from Task 2.

D. Task 4: Build a Disaster and Climate Change Risk Management Plan

Using the results from the previous activities, build a disaster risk management plan that collects all the measures (structural and non-structural) to reduce and manage risk and to control the expected impacts on third parties.

Box 6.1. Risk Assessments for Urban Settings

The "project" to which this Methodology refers includes both sector-specific infrastructure projects and broader multi-sectoral projects, including in urban settings. The general considerations and overall structure of a quantitative disaster and climate change risk assessment described above also apply to urban projects, and only minor perspective modifications need to be made.

Urban projects can often seem more complex than individual sector-specific projects because they include components from a variety of sectors (e.g., transportation, energy, water and sanitation, natural resources and housing). However, this provides urban projects with a more comprehensive, holistic, and multidisciplinary perspective that is crucial for proper risk management. Thus, all that is needed to tailor the risk assessment approach to urban settings and projects is a few additional details and a change in perspective:

- **Scope of analysis:** In most cases, the most obvious change is that the project is not a single infrastructure (or in a single sector), but a larger collection of assets, in number (i.e., neighborhoods, towns, cities, provinces) and in type (multisectoral). Thus, possible inter-dependencies between systems and assets becomes relevant and should be acknowledged and evaluated, as well as the correlation of losses among neighboring assets.

- **Resolution of inputs and results:** Generally, as the number of assets for which risk will be evaluated increases, the level of resolution of inputs and results decreases mainly due to the increase in computational requirements, but also due to the decrease in relevance of individual results within a larger portfolio point of view. In the application of the Methodology, this simply means using the "aggregated" or "topological" approaches described for a systems analysis in the following sections, which detail how to build a risk model (and its individual modules of hazard, exposure, and vulnerability). For large portfolios (e.g., complete city level), the probabilistic risk assessment approach is recommended because it allows for a robust incorporation of uncertainties and correlations.

- **Risk aggregation for analysis and reporting:** When risk is assessed for the project, two viewpoints should be used. The first relates to the complete portfolio, where risk is assessed for all individually exposed elements and then aggregated and analyzed as a whole to determine the overall portfolio risk. The second involves, in addition to reporting and analyzing the complete portfolio risk, analyzing the risk by sub-portfolios that can be built based on sectors or typologies. For example, in an urban intervention that includes all of the above-mentioned sectors, the city's road network could be a sub-portfolio for which risk is aggregated, reported, and analyzed. This would also be the case of the water and sanitation network, the telecommunications network, and the buildings (for buildings the use-sector could also be used to define sub-portfolios). This allows portfolio-specific analysis and a subsequent proposal of recommendations for risk mitigation.

- **Risk to third parties:** When risk to third parties is assessed, two viewpoints should be used. The first entails assessing the possibility of exacerbation of the risk to nearby assets that are within the urban area of analysis but not part of the intervention (e.g., if the intervention is rehabilitating a drainage channel in a neighborhood, incremental risk to neighborhoods upstream and downstream from the works should be evaluated). The second entails assessing the possibility of exacerbating risk to other nearby urban or rural settlements outside the urban center of analysis (e.g., if the intervention is to build a retaining wall to protect a city from an overflowing river, incremental risk to other towns or cities upstream and downstream of the city should be evaluated).

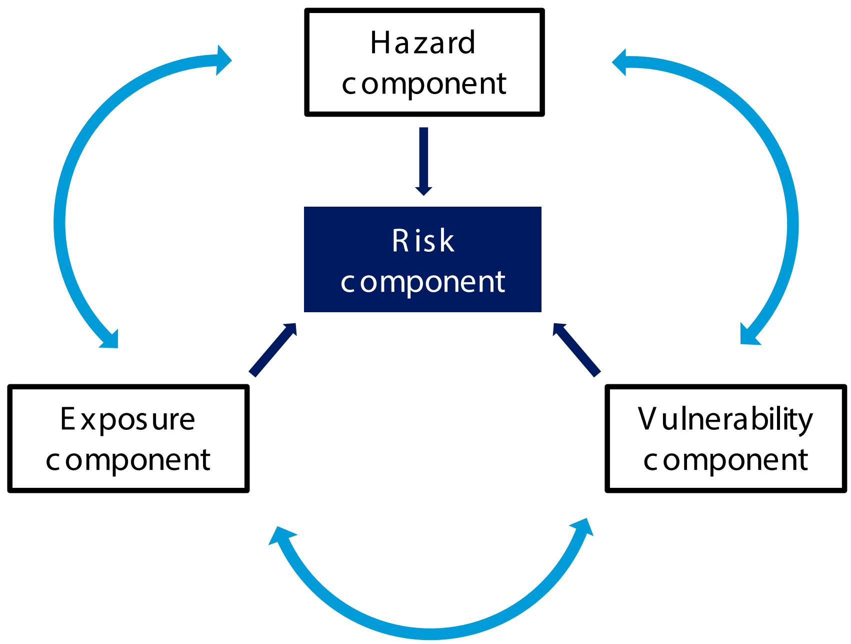
For example, the Emerging and Sustainable Cities (ESC) Program launched by the IDB in 2011 as a non-reimbursable technical assistance program, provided direct support to national and subnational governments in the development and execution of city action plans. The ESC used an integrated and interdisciplinary perspective to identify, organize and prioritize urban interventions to deal with the major challenges preventing sustainable growth of emerging cities in Latin America and the Caribbean. This cross-cutting approach was based on three bases: (i) environmental and climate change sustainability, (ii) urban sustainability, and (iii) fiscal and governance sustainability. Within the first basis, the studies on disaster and climate change risks (i.e. floods, droughts, earthquakes, landslides or coastal erosion) have proved to be key in planning and guiding the growth of many cities.

The document General Framework for the Development of Studies on the Reduction of Hydrometeorological Risks in Cities: lessons learned from the Emerging and Sustainable Cities iniciative in the light of the climate change challenges in Latin America and the Caribbean (García et al., 2019) provides details on this. This document shares a set of experiences and provides certain recommendations for the preparation of studies on risks generated by hydrometeorological sources in cities. It includes reflections and lessons learned from some of the cities with the highest risk levels in Latin America and the Caribbean, most of which are part of the ESC program, so that these learnings can be integrated in future studies led by the IDB or by other entities.

6.1.3 Architecture of a risk model

The purpose of quantifying risk is to calculate economic and/or human losses. The general architecture of a risk model mirrors the basic definition of disaster risk given in the Disaster and Climate Change Risk Overview section in Chapter 2 (Figure 6.2). This means, in general and for all hazards, integrating the three components discussed above (i.e., hazard, exposure, and vulnerability) to finally obtain risk. The way that the three components are integrated forms the core of the risk model.

Figure 6.2. Architecture of a Risk Model



In this model architecture, each component (i.e., hazard, exposure, and vulnerability) has its own individual module where corresponding technical considerations and evaluations are performed within each theme. However, one of the key attributes of the risk model is that although these modules are individual and separate from each other, all of them must allow correlation among themselves (represented by the circular arrows in Figure 6.2). In other words, independently of how each module is built, each module must provide a connection/communication mechanism with the others, in terms of both input and output formats, as well as technical logic and methods.

The hazard module aims to more precisely assess where and how each natural hazard could occur, studying the spatial extent, intensity and frequency of the hazard. Here, the way in which a hazard is modeled must have a spatial representation so that it can communicate with the exposure module and identify exposure to the hazards, and, in addition, it must be expressed in terms of a selected measure of intensity that corresponds to the measure of intensity used by the vulnerability module to determine damage.

The exposure module aims to build a geo-referenced database containing all the physical assets, as well as the population, that may be affected by a natural hazard. The hazard module will affect what is contained in this module. Here, the way in which exposure is modeled must have a spatial representation so that it can communicate with the hazard module and identify exposure to the hazards and, in addition, it must contain relevant information on asset or population characteristics that corresponds to the attributes used by the vulnerability module to determine damage.

The vulnerability module aims to more precisely assess the innate propensity of an exposed asset to suffer damages when facing the natural hazard(s) included in the hazard module. This means studying the inherent characteristics of exposed structures and people that make them more or less resistant to the demands imposed by the natural hazard(s) under study. Here, the way in which vulnerability is modeled must be expressed as a function of a selected measure of intensity of a hazard that corresponds to the measure of intensity used by the hazard module. In addition, it must be evaluated for the characteristics of the assets or population that correspond to the attributes represented in the exposure module to determine damage.

The risk module thus becomes the computing core of a risk model. It must integrate hazard, exposure, and vulnerability in a mathematical way that allows risk measures to be calculated. Risk measures include economic losses (in absolute dollar terms, or in relative or percentage terms, that is, as a percent of the total value of an asset or a portfolio) and social losses (number of lives lost, injured, or affected, in absolute or relative terms). Depending on the method used to calculate risk, these losses take different meanings, and additional risk measures may be obtained as well. We shall see this in more detail in the coming section.

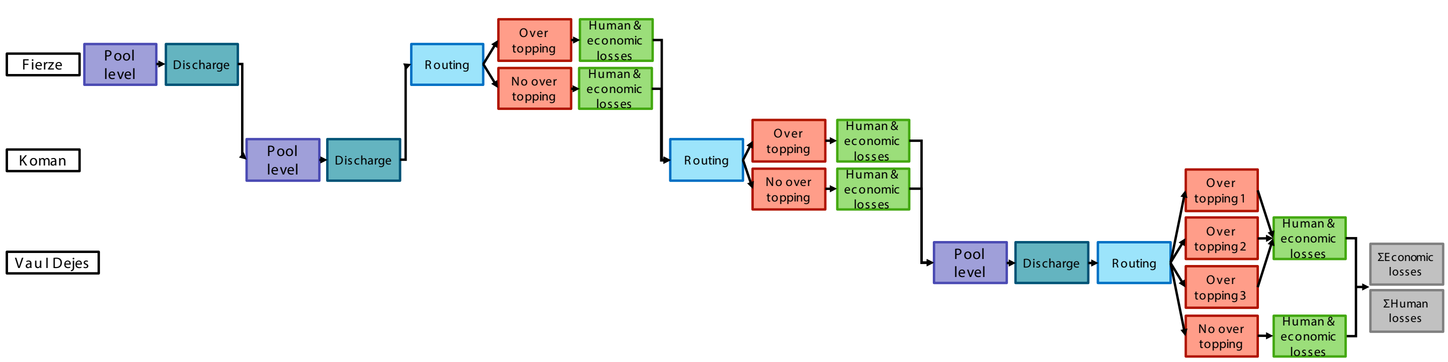
It is important to highlight again the need, on the one hand, to link the quantitative analysis to the results of the qualitative analysis, and on the other hand, to carry out a type of quantitative analysis that is consistent with the availability of data, the uncertainties of climate change and population dynamics, the existence of tolerability and/or acceptability criteria in the sector or subsector, and the potential dependence of the technical and economic viability of the whole project. For illustrative purposes, the example started in Section 5.2.6 is continued next.

6.1.3.1 Example: Complete Qualitative Risk Assessment leading to a Quantitative risk Assessment (Escuder-Bueno et al., 2016) - Continued

In the first part of the example presented in Section 5.2.6, it was determined that the overtopping failure modes required further study and thus a quantitative risk assessment was suggested. To conduct the quantitative risk analysis, a risk model of the dam system was built to include the hydrological demands (the hazard), the system response or failure modes (vulnerability), and the consequences (risk - economic and human losses).

The risk model (Figure 6.3) uses influence diagrams and event trees to compute failure probability and risk (Escuder Bueno and González Pérez, 2014). The resulting risk model is divided in three sub-models, one for each reservoir (Fierze, Koman and Vau I Dejes), where downstream reservoirs include the outflows from upstream reservoirs (in failure and non-failure cases).

Figure 6.3. Risk model (Escuder-Bueno et al., 2016)

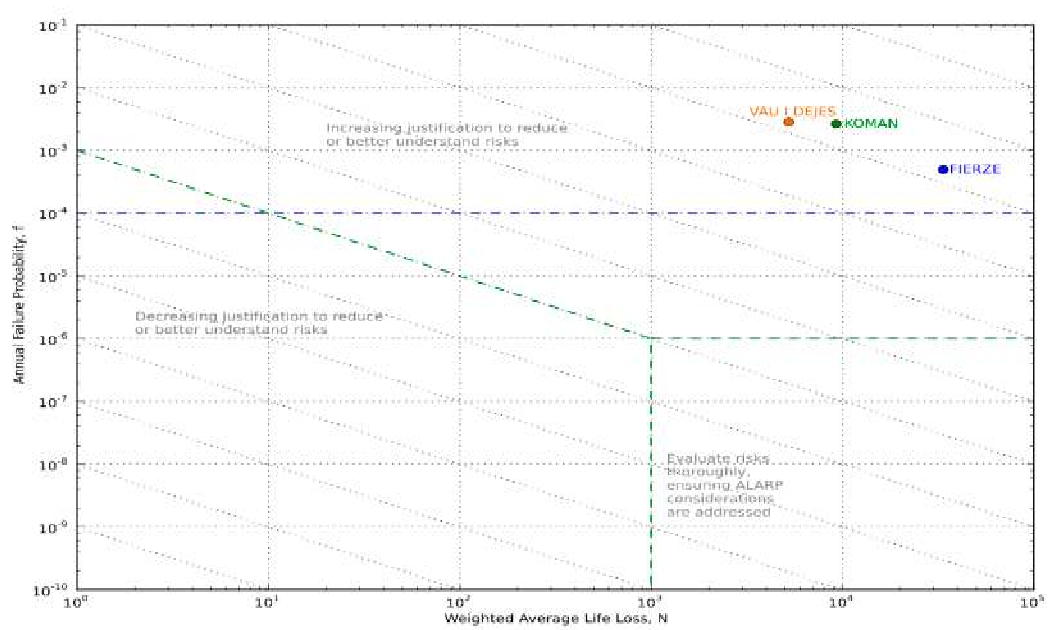


According to this, the loading conditions for each sub-model are introduced first (in the blue nodes) to obtain flood routing results (maximum pool level and outflow) for each possible combination of initial conditions in the three reservoirs: probability of initial pool level in the reservoir, incoming discharge hydrograph for different return periods, and reliability of outlets/spillways. A total of 10,321,920 flood routing cases were analyzed. These results are then used along with the following inputs to estimate failure probability (red nodes): failure hydrographs for each reservoir, and fragility curves that relate pool level with overtopping failure probability. Finally, the data on consequences for failure and non-failure cases are introduced in the green nodes: relationships between outflow discharge and consequences (economic and human losses) for failure and non-failure cases.

All these inputs had already been gathered in the documentation review and the working sessions conducted in the qualitative risk assessment. With all this, the risk calculation is performed as follows: the probability of each branch of the event tree is obtained by multiplying all the conditional probabilities of the sub-branches, and finally, failure probability and total risk is obtained by adding up the results of all the branches.

To analyze and evaluate the risk results, these were plotted in the United States Bureau of Reclamation (USBR) tolerability graph (USBR, 2011). The USBR tolerability guidelines are based on f-N graphs, which represent the relationship between failure probability (f) and average loss of lives (N), as can be seen in Figure 6.4. This graph sets a first limit on the annual probability of failure (a horizontal line) on a value of 10^{-4}, a number that is related to the individual risk, to the public responsibility of the project owner and to the protection of the image of the organization. A second limit on the average annual life loss is set on a societal risk of 10^{-3} (a vertical line). These limits define different areas. In general, the further the risk results are from the limit lines towards the top and top-right corners of the graph, the more justified risk reduction measures are. Similarly, the further away the risk results are from the limit lines towards the bottom and bottom-left corners of the graph, the less justified risk reduction measures are. As can be seen from Figure 6.4, the analyzed dams present high risks (high probabilities of failure and large societal consequences located in the top-right corner); thus, action is justified to reduce this risk.

Figure 6.4. Risk estimates plotted versus USBR tolerability guidelines (Escuder-Bueno, 2016)



Furthermore, it was also important to quantify the impact of uncertainty on the baseline risk estimates focusing on how it may affect the decision making for possible risk-mitigation measures. The main uncertainties identified in the input data are related to the availability of hydrological data, to the complexity of flood routing rules and to the estimation of consequences (economic and human losses). Thus, an uncertainty analysis was performed on the hydrological data, the initial pool levels in the reservoirs, and the different flood routing rules. The results showed that the main impact in the results was produced by the uncertainty in the hydrological data. Finally, these results were used to propose different risk-mitigating options and the quantitative risk model was used to evaluate the following:

- Emergency Action Plan.
- Strict maintenance program of gates.
- Restoration of Spillway 3 in Fierze.
- New Spillway 5 in Fierze.
- New Spillway 5 in Koman.
- New water level limit in Koman to restrict outflow in Fierze as part of an overall revision and improvement of flooding operating rules (discharges).
- Rehabilitation of bottom outlet in Qyrsaq.

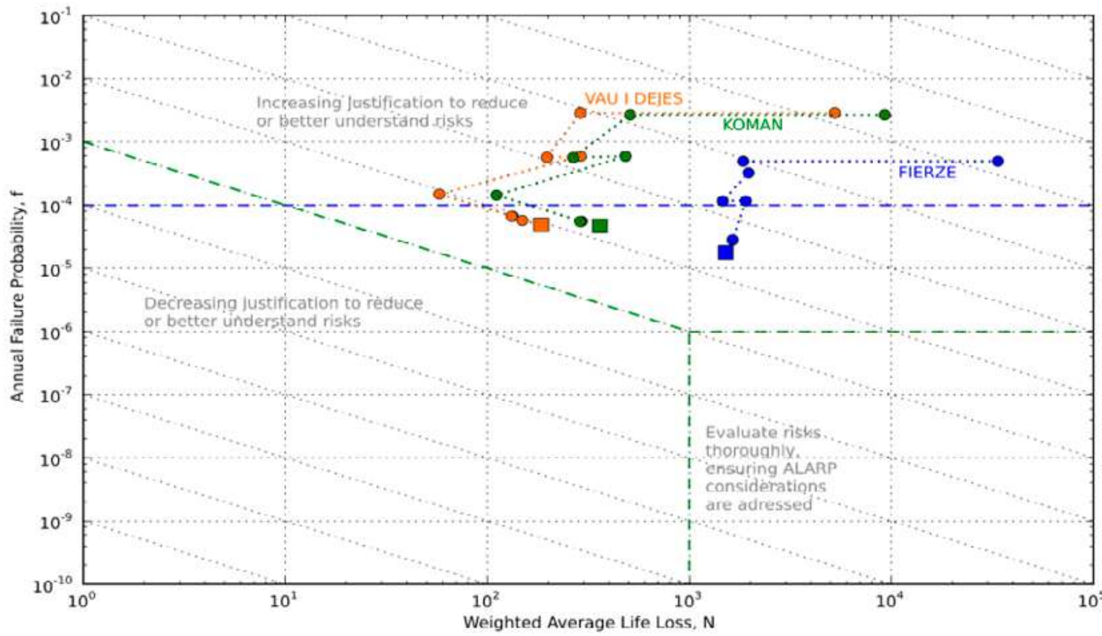
These structural and non-structural measures were introduced and tested in the quantitative risk model and were prioritized by the reduction of human losses, following the societal efficiency principle. This was done following an iterative process where in each step of the process the risk is recomputed for each measure and the option with the lowest social risk is chosen (see Table 6.1). Figure 6.5 shows the process followed for introducing risk mitigation measures for each dam in the f-N graph.

The first measure implemented in the process is the Emergency Action Plan, highlighting the importance in this system of dams of developing proper emergency procedures, warning systems and education programs to decrease loss of life downstream. The second measure is the improvement of the maintenance and control of the spillway gates. Just with these two measures, human losses in the dam system are reduced by almost two orders of magnitude. Moreover, the new spillways in Koman and Fierze and the recovery of spillway 3 in Fierze would help to reduce the risk an additional order of magnitude. Lastly, the rehabilitation of the bottom outlet in the Qyrsaq dam further reduces the risk, although its effect is less drastic.

Table 6.1. Obtained sequence of risk mitigation measures (Escuder-Bueno, 2016)

Step	Measure
1	Emergency Action Plan
2	High maintenance program of gates
3	New Spillway 5 in Fierze
4	New Spillway 5 in Koman
5	Restoration of Spillway 3 in Fierze
6	New limit water level in Koman
7	Rehabilitation of bottom outlet in Qyrsaq

Figure 6.5. Changes in risk in a f-N graph following the proposed implementation sequence (Escuder-Bueno, 2016)



In conclusion, the risk assessment results show that to effectively mitigate the existing risk to the system of dams, both structural (upgrading or building new structures) and non-structural (better gate maintenance and control, better compilation of monitoring data, clearer flood routing rules, and proper emergency procedures) measures are needed and that the development of a dam safety culture within the project owner and all stakeholders is key.

The following sections provide technical specificities and details on the methods and models to build the risk model. First, available risk methods and approaches are described. Second, hazard-specific risk models are described, and third, results are analyzed and a disaster and climate change risk management plan is built.

6.1.4 Risk assessment

6.1.4.1 Selecting a risk assessment approach

Since the risk module links all the individual modules of hazards, exposure, and vulnerability, the methods for the evaluation of risk correspond to those of the independent modules. This section will provide guidance on selecting a risk assessment approach. Table 62 summarizes two methods for risk assessments and three additional special approaches.

Furthermore, according to Morales-Torres et al. (2019), the evaluation of uncertainty plays an important role in the evaluation and management of complex structural systems. In general, two sources of uncertainty are considered:

- Natural uncertainty or randomness: Produced by the inherent variability in natural processes. An example is the variability of the loads on the structure, such as variability in the potential flood magnitudes. This type cannot be reduced, although it can be estimated.

- Epistemic uncertainty: Resulting from not having enough knowledge or information on the analyzed system. This lack of information can be produced by a deficiency of data or because the structure's behavior is not correctly represented. The more knowledge that is available about a structure or system, the more this type of uncertainty can be reduced.

Dealing with natural and epistemic uncertainty has been one of the main discussion points in quantitative risk analysis for infrastructure safety management. The most common approach is addressing separately both types of uncertainty through a probabilistic analysis, obtaining a probabilistic distribution of risk results based on epistemic uncertainty variations. Thus, it is important to highlight that in either fully or simplified probabilistic approaches (see Table 61), only the random uncertainty is typically integrated into the calculations, whereas epistemic uncertainty requires a second and separate level of analysis.

The selection of a risk assessment method depends on the needs of the specific project. It usually relates to the availability of data for the hazard and the project, the availability of models for the hazard and the project type, time and resource constraints for the assessment, the type of analysis (for single or multiple elements), the size and criticality of the project, the level of detail required for the results, the type of results or outputs expected, and the type of decisions to be made with the results. Most of these refer to a trade-off between computational efforts and level of detail. However, of all these, probably the most important one is the expected type of decision to be made. This refers to determining what knowledge is needed: the overall risk of a city, or the precise expected damages for one or two critical structures? Is it necessary to know the risk for small and large events, or for a specific event or intensity? Will general risk reduction strategies be proposed, or detailed changes to the design? The approaches described in this Methodology cover a wide range of needs and requirements. None of the approaches is recommended over the others, since this must be analyzed on a project-by-project basis to select the most appropriate approach.

Table 6.2. Risk Assessment Approaches

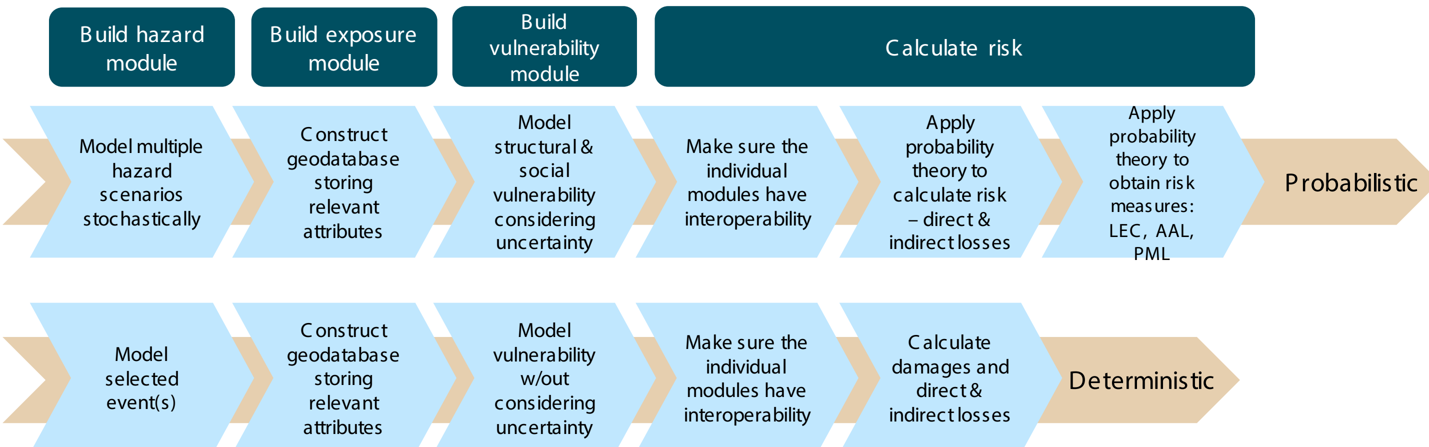
Method	Description	
Probabi-listic Risk Assess-ment	A probabilistic risk assessment aims to address some of the uncertainties inherent to disaster risk. These uncertainties arise from: (i) the limited availability of historical data, (ii) the rarity of catastrophic events, (iii) the small observation window of disasters, and (iv) changing climate trends, among others (ERN-AL, n.d.a). In a probabilistic risk assessment, the components that make up risk (mainly hazard and vulnerability) are modelled probabilistically and then mathematically integrated in a probabilistic manner, formally acknowledging and incorporating uncertainty throughout the model. In this way the model can statistically represent the probability of all possible events, even those that have not yet occurred, making it a prospective model. This type of assessment can be applied to both individual projects and larger portfolios (e.g., cities, systems, and networks, at the regional or the country level), as long as the appropriate adjustments are made to the model to respond to the level of detail required in each case. Three general types of probabilistic assessments are described here but note that other types may be created by combining these in different manners. For instance, models can be created were some components are treated as fully probabilistic, others as simplified probabilistic and others as deterministic.	Fully Probabilistic Assessment: For the hazard module, tens or hundreds or thousands of individual stochastic events are generated following probability and statistical theory, all of which are used in the calculation. For the vulnerability module, structural behavior and response are given a probabilistic treatment determining probabilities of damage and associated uncertainty. For the risk module, the Total Probability Theorem is used to integrate the stochastic events and the values of hazard intensity, exposure, and vulnerability to calculate expected damages and the associated probabilities propagating uncertainty throughout the model. The fully probabilistic treatment of the risk calculations results in obtaining the probability distribution of losses. From this, the risk measures of the loss exceedance curve (LEC), as well as the average annual loss (AAL) and probable maximum losses (PML) are obtained. See CAPRA's Probabilistic Evaluation of Natural Hazards in https://ecapra.org/node/172. This approach may be difficult to implement for individual infrastructures given that it will be time and resource consuming to determine the probability functions of all the components of a risk model for a specific infrastructure; however, it may be more appropriate for portfolio analyses where less detail is required for individual elements, for example urban settings.
		Simplified Probabilistic Assessment: in the simplified method, instead of stochastic simulations, only a few return periods of the hazard are modelled. The return periods are defined through different methodologies. Some of the most frequent include: (i) the statistical analysis of instrumental measures of the events that trigger the hazard (rains, earthquakes), (ii) geomorphological analysis of past events, and (iii) statistical analysis of historical data (surveys, data of newspapers). The return periods are selected trying to cover the spectra of possible events, from high frequency to medium and low frequency events. The losses for the considered hazard return periods are estimated combining such outputs with the vulnerabilit y module (e.g., vulnerability curves or fragility curves applied in a probabilistic manner). Because the hazard module does not meet the requirements to calculate risk using the fully probabilistic method, the aleatory uncertainties associated with the hazard are not propagated through the entire model. This still allows for the calculation of the AAL if a few return periods are used (usually, five or more return periods are required). Likewise, a proxy of the LEC and PML can be obtained, applying extrapolation from the results of the limited risk scenarios estimated, but this incorporates additional uncertainty to the results (see the multicolor Manual from UK as an example). This approach may be better suited for individual infrastructures given that the simplified method of calculation allows for greater details in each component.
		Mixed Probabilistic-Deterministic- Assessment: in this approach Some components of the risk assessment are estimated probabilistically and others deterministically. For instance, the following two cases may occur: (i) the hazard is estimated probabilistically, where only a few hazard scenarios with associated return periods are utilized (simplified probabilistic) and the vulnerability deterministically, or (ii) the hazard is estimated deterministically and the vulnerability probabilistically, a common approach for landslide risk. Because some of the modules do not meet the requirements to calculate risk using the fully probabilistic method, the aleatory uncertainties associated with the hazard and the uncertainties in the response of the structures are not propagated through the entire model. For the first case, and similarly to the simplified probabilistic approach, the AAL may be obtained and the LEC may be estimated through extrapolation of the loss values obtained for the considered hazard return periods. This approach can be used to estimate the response of complex infrastructures where finite element models are required and the modelling of a large number of scenarios of the structural response is impractical. Likewise, in the modeling of complex risk models, a combination of probabilistic and deterministic method could be more viable.

Method	Description	
Determi-nistic Risk Assess-ment	In a deterministic risk assessment, there is no consideration or incorporation of uncertainty in the risk model and specific individual events (could be one or more) are evaluated using empirical data. Typical deterministic risk assessments include recreating and calculating risk for historical events and modeling and calculating risk for worst-case scenarios. The calculated losses have no associated uncertainty and thus are deterministic. It should be noted that under climate change, loss of stationarity might generate new types of hazards and larger events, and this should be acknowledged. This approach may be used in conjunction with a probabilistic risk assessment to validate and calibrate the modeling. This type of assessment is better suited for individual projects since uncertainties become more important to address in larger portfolios.	Past Historical Event: Data on hazard, exposure, and vulnerability may exist for a single past event which could be modeled and recreated. For the hazard module, data on the event are collected and recreated either by mapping or modelling. For the exposure and vulnerability modules, either past exposure and vulnerability during the event may be recreated, or present-day exposure and vulnerability may be built to analyze what would happen today if the past hazardous event were to happen again. For the risk module, and because there is no incorporation of uncertainties in the model, the damages and losses are determined directly from the given event and from the exposure and vulnerability characteristics assumed as a given. This approach can also be used to help the public better understand the concept of risk since it has occurred and may be remembered.
		Worst-case Event: Risk can also be computed for a hazardous event representing extreme or worst-case conditions. For the hazard module, basic set-up data for the event are used to model the event. For the exposure and vulnerability modules, present-day exposure and vulnerability are built to analyze what would happen if the worst-case hazardous event were to happen today. For the risk module, and because the model does not incorporate uncertainties, the damages and losses are determined directly from the given event and from the vulnerability characteristics assumed as certain. This approach is typically used to test extreme scenarios.
Robust Decision Making (RDM)	This type of assessment is better suited for large portfolios such as systems or networks, where more high-level actions or recommendations are appropriate. In an RDM-type risk assessment, uncertainty in a risk model, more specifically deep uncertainty, is addressed and is actually the main focus of the approach, although it is not explicitly quantified as in a probabilistic risk assessment. Robust Decision Making (RDM) or Decision Making Under Deep Uncertainty (DMDU) defines from the beginning multiple scenarios of both demand solicitations (e.g. hazard scenarios, climate change projections, project vulnerability) and potential actions which are usually more on the strategic level, and tests all of them evaluating the risks and benefits. At the end it pursues an "agreement on potential actions" by selecting robust actions that will maximize benefits across the likely range of potential conditions.	
Historical timeline analysis[20]	This type of risk assessment mostly applies only for the agriculture sector for which detailed risk assessment methods are not very common as the current state of the art is still in development. This risk approach builds a timeseries of historical events (mainly of hydrometeorological hazards) and a parallel timeseries of agricultural production and attempts to establish causation between the two and estimate average annual economic losses from this.	
Exposure assess-ment	Although this is not a risk assessment, this analysis can work as a simplified quantitative assessment. This analysis, which lacks the vulnerability component, consists of overlapping the hazard and exposure modules to analyze what is exposed to the hazard(s).	

20 This type of analysis is a simplified risk assessment method used specifically for the agriculture sector. This method is treated as a special case in this Methodology given that more detailed disaster risk models for the agricultural sector are still very new and under development; hence, the other more standardized approaches detailed in this Methodology for the hazard, exposure and vulnerability components do not necessarily always apply to this sector.

The activities that comprise each of the two main approaches (probabilistic and deterministic) are summarized in Figure 6.6 below.

Figure 6.6. Summary of Activities to Develop a Risk Assessment



Probabilistic Risk Assessment

This type of assessment provides much more information on potential losses, including the likelihood that losses occur (i.e., probability distribution of losses). It is the most resource-intensive of the two approaches. Two large groups of activities can be identified: the first includes the building of the three individual modules of hazard, exposure, and vulnerability, and the second focuses on performing the risk calculations. Within the first group, the three activities it includes are: (1) model hazard probabilistically, (2) construction of a geodatabase storing all relevant attributes of the exposure, and (3) modelling of structural and social vulnerability probabilistically considering uncertainties. Within the second group, the three remaining activities are: (4) ensuring that the hazard, exposure, and vulnerability modules are appropriate and interoperable, (5) applying an appropriate probabilistic mathematical model to integrate all modules and calculate direct and indirect losses, and (6) using the probabilistic framework to calculate the risk measures of the LEC, AAL, and PML.

1) Model hazard probabilistically:

This activity involves constructing a probabilistic hazard model for all the hazards that can impact the project. This activity is explained in detail in the section Quantification of the hazard component, including how to incorporate climate change effects. In summary, the following conditions must be met for each type of probabilistic assessment:

- For the fully probabilistic approach, a set of mutually exclusive and collectively exhaustive stochastic scenarios must be generated. For hydrometeorological hazards, these scenarios must incorporate climate change effects and uncertainty.

- For the simplified-probabilistic approach, probabilistically integrated hazard intensity values with associated return period are used. For hydrometeorological hazards, these hazard intensity values must incorporate climate change effects.

- For the mixed probabilistic-deterministic approach, determine whether the hazard module will be treated as fully probabilistic, as simplified probabilistic or as deterministic, and in the first two cases follow the respective cases.

2) Construct an exposure geodatabase:

This activity involves constructing a geo-referenced database of exposed assets (including buildings and infrastructure, as well as population) that gathers all of the characteristics that are relevant to evaluate vulnerability to natural hazards. This activity is explained in detail in the section ***Quantification of the exposure component***.

3) Model structural and social vulnerability probabilistically:

This activity involves constructing a probabilistic vulnerability model for all the physical assets that are part of exposure, as well as for the exposed population. This activity is explained in detail in the section ***Quantification of the vulnerability component***. The following conditions must be met for each type of probabilistic assessment:

- For the fully probabilistic approach, uncertainties in the engineering analysis (for physical assets) and in the social analysis (for the population) must be incorporated.

- For the simplified-probabilistic approach, although the uncertainties in the engineering and social analyses may be incorporated, usually because of the simplified nature of this type of assessment, the uncertainties are not part of the vulnerability module. This means that only average values of damage estimations (a deterministic approach for the vulnerability module only) are used.

- For the mixed probabilistic-deterministic approach, determine whether the vulnerability module will be treated as fully probabilistic, as simplified probabilistic or as deterministic, and in the first two cases follow the respective cases.

4) Ensure that individual modules have interoperability:

This activity involves reviewing the completed individual modules and making sure there is compatibility and interoperability among them. The following conditions must be met:

- For the hazard module: the outputs of the hazard model that become inputs to the risk model consist of a set of mutually exclusive and collectively exhaustive stochastic hazard scenarios (for a fully probabilistic assessment) or a set of integrated hazard maps (for a simplified-probabilistic assessment), where each one has a spatial representation (GIS format), a numeric representation of the selected intensity, and an associated frequency of occurrence. The spatial representation is needed so that the hazard and exposure modules can communicate; this means having GIS layers (typically in a raster format) for each individual hazard scenario with a proper georeferentiation and coordinate system compatible with that of the exposure module. For the second characteristic, an appropriate intensity measure must be selected that best correlates with physical damages for the hazard and vulnerability modules to communicate. This means expressing the hazard in terms of a measure of intensity that corresponds to the same measure of intensity used by the vulnerability module to determine damage. Lastly, an associated frequency of occurrence is needed for the risk module to calculate risk using probability theory.

- For the exposure module: the output of the exposure module that becomes an input to the risk model consists of a database of all exposed assets and population that has a spatial representation (as it is georeferenced, it is also called a geodatabase) and that stores all relevant physical and social characteristics. The first characteristic refers to the compatibility between the hazard and exposure modules explained above. The second characteristic is needed so that the exposure and vulnerability modules can communicate. It refers to storing the physical structural characteristics (for infrastructure), such as constructive type, structural system, general dimensions, geometry, condition, and others, and social characteristics (for the exposed population) that directly correspond to the vulnerability functions contained in the vulnerability module that provides information about the expected damages.

- For the vulnerability module: the outputs of the vulnerability module that become inputs to the risk model consist of a vulnerability relationship that: (i) is built for specific physical characteristics of the exposed elements, (ii) provides estimated damages as a function of a specific hazard measure of intensity, and (iii) has an associated uncertainty. The first characteristic refers to the compatibility between the vulnerability and exposure modules explained above. The second characteristic refers to the compatibility between the vulnerability and hazard modules explained above. The third characteristic is needed for the risk module to calculate risk using probability theory.

5) Apply an appropriate probabilistic mathematical model to integrate all modules and calculate direct, indirect, and total losses:

In this activity, the three individual modules described above are mathematically integrated. The risk calculation procedures for the three types of probabilistic risk assessments presented in Table 6.1 (fully probabilistic, simplified probabilistic and mixedprobabilistic-deterministic) are presented next. Uncertainties associated with the model itself should be incorporated with other methodologies (i.e., the qualitative analysis to identify different scenarios that should be considered in the model).

Fully Probabilistic Risk Assessment:

This framework is used by the CAPRA platform. (For a full description and details, please refer to ERN-AL (n.d. a, n.d. f), Cardona et al. (2015), Ordaz (2000), and CAPRA's Probabilistic Evaluation of Natural Hazards in https://ecapra.org/node/172.) According to this framework, the basic premise of a probabilistic risk calculation is that the **loss** ($\mathcal{L}$ or ℓ) is an uncertain quantity and, as such, should be treated as a random variable for which probability theory applies. It is usually assumed that the **loss**, $\mathcal{L}$, follows a Beta distribution.

The random variable **loss**, $\mathcal{L}$, can be expressed through different events (events in the context of probability theory), which are specific realizations of the **loss**, $\mathcal{L}$, for example: ℓ=$2,000 or $500< ℓ <$7,500 , etc. Ideally, the objective of a probabilistic risk assessment would be to find the probability of having a certain loss, or $\mathcal{P}(\mathcal{L})$. However, because these loss events can be completely arbitrary, finding $\mathcal{P}(\mathcal{L}=\ell)$ is not straightforward. Hence, it is appropriate to define the random variable **loss**, $\mathcal{L}$, in terms of a set of **base events** that are indeed known and apply the Total Probability Theorem to find $\mathcal{P}(\mathcal{L})$ defined through exceedance probabilities rather than punctual probabilities.

The **base events** correspond to hazard events, which are known, for which the probabilities of ℓ can be found (for hydrometeorological hazards, these hazard events must incorporate climate change effects and uncertainty). Thus, if the entire sample space of the random trial for **loss**, $\mathcal{L}$, is subdivided into the base events, finding the probability of ℓ becomes easier as it consists of adding all the intersections of the known base events and the loss event. These intersections, in probability terms, can be calculated as conditional probabilities, that is, multiplying the probability of having ℓ given that base event e occurred multiplied by the probability of occurrence of event e. Finally, to find the probability of ℓ, all the conditional probabilities are added. This is the Total Probability Theorem. To be able to apply it, it is necessary that all base events are collectively exhaustive (i.e., they cover the entire sample space, meaning that they cover the entire universe of possibilities of base events) and mutually exclusive (i.e., there are no intersections between base events, meaning that separate base events cannot occur simultaneously). Equation 61 shows the general equation of the Total Probability

Theorem applied to calculate the probability of a loss event ℓ.

Equation 6-1 $$P(\ell) = \sum_{i=1}^{n} P(\ell|e_i) \cdot P(e_i)$$

where ℓ is a loss event, $\mathcal{P}(\ell|e_i)$ is the probability of having said loss given that the i^{th} event, e_i occurs, $\mathcal{P}(e_i)$ is the probability of having event e_i and n is the total number of hazard base events (or scenarios).

In the context of disaster risk due to natural hazards, risk is expressed as the **exceedance** of losses (not the occurrence). Thus Equation 61 is modified to obtain the loss exceedance rates, taking the form of Equation 6-2 which becomes the basic risk equation:

Equation 6-2 $$\nu(\ell) = \sum_{i=1}^{n} P(\mathcal{L} \geq \ell|e_i) \cdot F_{e_i}$$

where $\nu(\ell)$ is the loss exceedance rate of loss ℓ, $P(\mathcal{L} \geq \ell|e_i)$ is the probability of exceeding loss ℓ given the i^{th} hazard event occurred, e_i, F_{e_i} is the annual frequency of occurrence of the i^{th} hazard event, e_i, and n is the total number of hazard events (or scenarios). The loss exceedance **rate** is a function of the loss, and as such it has a graphic representation called the loss exceedance curve, or LEC. The LEC has all the necessary information on the occurrence process of losses in probabilistic terms. Note that the inverse of the exceedance rate, $\nu(\ell)$, is the return period, *RP*, of loss . Additionally, note that it is the **loss**, $\mathcal{L}$, that is a random variable, and not the loss' annual exceedance rate, $\nu(\ell)$, which is provided by the LEC.

Now, to calculate the probability of having a loss given a hazard event $P(\mathcal{L} \geq \ell|e_i)$(in Equation 62), the probability distribution of **loss** $\mathcal{L}$ (assumed Beta) for each hazard scenario is used, where it is a joint probability distribution of the probability distribution of the hazard intensity and the probability distribution of the damage ratio (vulnerability). Thus, this joint probability distribution is calculated through the following equation, which reveals the composition of risk into hazard and vulnerability:

Equation 6-3 $$f(\ell|e_i) = \int_0^{\infty} \underbrace{f(\ell|s)}_{Vulnerability} \cdot \underbrace{f(s|e_i)}_{Hazard} \, ds$$

where $f(s|e_i)$ is the probability distribution function of loss ℓ given the i^{th} event, e_i. The vulnerability component, $f(\ell|s)$, is the probability distribution function of the loss, ℓ, given an intensity of the hazard, *s*; therefore, the vulnerability module needs to have a probabilistic treatment that incorporates uncertainty. The hazard component, $f(s|e_i)$, is the probability distribution function of the hazard intensity, *s*, given a hazard event, e_i; therefore, the hazard module needs to have a probabilistic treatment that incorporates uncertainty. With Equation 63 and assuming a Beta distribution of the loss, it is possible to determine the probability distribution function for the loss for an individual exposed element.

If multiple elements are exposed and risk is to be calculated for these (e.g., in a city where the entire urban exposure is being assessed, or if an infrastructure project includes several infrastructure elements), Equation 6-3 is applied individually to each exposed element and the total loss for the i^{th} hazard event is obtained by adding individual losses on the exposed elements. However, because these individual losses are random variables, the addition must be performed using appropriate arithmetic for random variables, where the sum is conducted over the statistical moments:

Equation 6-4 $$E(\ell|e_i) = \sum_{j=1}^{m} E(\ell_j)$$

Equation 6-5

$$\sigma^2(\ell|e_i) = \sum_{j=1}^{m} \sigma^2(\ell_j) + 2\sum_{k=1}^{m-1} \sum_{j=2}^{m} COV(\ell_k, \ell_j)$$

where $E(\ell|e_i)$ and σ^2 are the expected value and variance, respectively, of the loss ℓ for the i^{th} hazard event, e_i. The term is the total number of exposed assets in the evaluation portfolio. The $COV(\ell_k, \ell_j)$ is the covariance between exposed elements *k* and *j*; this term accounts for the correlation of losses between exposed elements, a critical component of a fully probabilistic assessment. However, it may be difficult to determine this covariance, so a correlation coefficient ρ_{kj} may be assumed and used; the covariance term then becomes $COV(\ell_k, \ell_j) = \rho_{kj}\sigma(\ell_k)\sigma(\ell_j)$. Applying these equations, the aggregated expected value and variance is determined for the complete portfolio of analysis, and these are then used to obtain the probability distribution $f(\ell|s)$ of the sum of the losses (also assumed Beta) for each hazard scenario.

Finally, after obtaining the probability distribution of losses for any hazard scenario through Equation 63,the contribution of all hazard events to the loss exceedance rates are computed and aggregated using
Equation 6-2.

In summary, the sequence of calculations, following Equations 6-1 through 6-5 is:

i. Take an event (with an associated probability of occurrence) from the hazard module: this will be the *i=1* hazard event. Superimpose the exposure geodatabase with this hazard event, determine the estimated value of hazard intensity felt at the site of one exposed element (this will be the *j=1* exposed element) and determine the estimated damage level (mean damage ratio) for this exposed element (for the given hazard intensity value) from its corresponding vulnerability relationship. At this point both direct and indirect losses (the latter include losses due to loss of functionality that lead to business interruption) must be included in the vulnerability module. Calculate the probability distribution of the loss for element *j* under hazard event *i* using Equation 6-3 and assuming a Beta distribution for the loss.

ii. If there is more than one exposed element, repeat (i) individually for all the remaining j^{th} exposed elements (until reaching m), use Equation 6-4 and Equation 6-5 to obtain the aggregated expected value and variance of the loss for the *i=1* hazard event and determine the probability distribution of the sum of the losses.

iii. Repeat steps (i) and (ii) for the remaining i^{th} hazard events in the hazard module until reaching n . Use Equation 6-2 to probabilistically integrate the losses calculated for individual hazard events using the frequency of occurrence of the hazard events as a weighting factor. The LEC is obtained.

Aside from calculating the losses in absolute terms, it is useful to normalize them to get a better representation of the level of risk. For this a risk ratio is used. To calculate the loss ratio, which is more representative of the risk, he total loss is divided by the sum of the structure, contents, and inventory values of the asset(s). This expresses risk as a percentage of an asset's or portfolio's replacement value.

Simplified Probabilistic Risk Assessment:

Other platforms, such as Hazus by FEMA, use this approach (Please refer to FEMA (n.d.a; n.d.b; n.d.c.) for the full description and details.). Unlike the fully probabilistic risk calculation, where individual stochastic hazard events form the basis of the Total Probability Theorem used to completely characterize the probability distribution of losses, in a simplified probabilistic risk calculation, losses are directly computed for specific and discrete hazard intensity scenarios (not events) with an associated return period. These discrete losses are then individually reported, and only then can the average annual loss be determined directly, although an estimated LEC curve may be derived using extrapolation (see Activity 6). This is a major difference between a fully probabilistic and a simplified probabilistic risk calculation: the former is able to provide the detailed and complete probability distribution of losses (from which a wide range of risk measures can be computed) whereas the latter is only able to provide discrete loss estimates for determined hazard intensity values with a return period and an estimated (or proxy) distribution of losses (from which the average annual loss can be directly computed and the LEC and PML curves can only be estimated by extrapolation assuming that the probability of the hazard is equivalent to the probability of the risk). This creates less precision in the shape of the curve and in the estimation of the benefits.

The term simplified probabilistic risk calculation refers to the manner in which the hazard, exposure, and vulnerability modules are mathematically integrated and ultimately to how losses are calculated. Thus, although the hazard module does include probability indirectly through the use of return periods, its subsequent integration with the exposure and vulnerability modules and the calculation of losses does not provide the complete probability distribution of losses. Having said this, although the incorporation of uncertainty and probability in the vulnerability module should be a part of any probabilistic risk assessment (fully or simplified), usually simplified probabilistic assessments do not apply it and only use mean damage estimations.

In summary, the sequence of calculations, following the same logic as for a fully probabilistic calculation, is:

i. Take a hazard intensity value (with an associated exceedance rate or return period) from the integrated hazard module: this will be $i=1$ the return period. Superimpose the exposure geodatabase with the spatial distribution of the integrated hazard, determine the estimated value of hazard intensity felt at the site of one exposed element (this will be the $j=1$ exposed element) and determine the estimated damage level (mean damage ratio) for this exposed element (for the given hazard intensity value) from its corresponding vulnerability relationship. At this point both direct and indirect losses (the latter include losses due to loss of functionality that lead to business interruption) must be included in the vulnerability module.

ii. If there is more than one exposed element, repeat (i) individually for all the remaining j^{th} exposed elements and add up the expected values and variances of the loss for all exposed elements for the $i=1$ return period.

iii. Repeat steps (i) and (ii) for the remaining i^{th} return periods in the integrated hazard module until reaching *m*.

Mixed Probabilistic-Deterministic Risk Assessment:

This approach is commonly used for hazards that are more complex to completely characterize probabilistically. Thus, a combination with deterministic approaches is needed (i.e., landslide risk). First, it must be determined how the risk model is going to be built, establishing which components will be treated probabilistically (and within this, if fully or simplified) and which deterministically. Two cases may occur: (i) the hazard is estimated probabilistically and the vulnerability deterministically, or (ii) the hazard is estimated deterministically and the vulnerability probabilistically.

For the first case where the hazard is treated probabilistically and the vulnerability deterministically, the calculation of risk will allow for the LEC to be obtained, either directly (if treated as fully probabilistic) or via proxy (if treated as simplified probabilistic). Depending on the selected probabilistic treatment for the hazard (fully or simplified), the corresponding calculation method detailed above should be followed. The only change to these would be to consider the vulnerability component as deterministic disregarding any variance or uncertainty.

For the second case where the vulnerability is treated probabilistically and the hazard deterministically, the calculation of risk will not allow for the LEC to be obtained, only punctual results. Losses will be obtained for varying responses of the structure (vulnerability) for a predefined hazard condition. For the vulnerability component, sector and hazard-specific methods determine the risk calculation procedure, but this usually involves detailed structural modelling including structural reliability theory (Johansson et al., 2013), finite-elements and Monte Carlo simulations, among others.

6) Calculate the risk measures:

In this activity, the risk calculation results from the previous activity are used to obtain specific risk measures or metrics. The calculation of the main risk metrics of the two types of probabilistic risk assessments presented in Table 6.1 (fully probabilistic, simplifiedprobabilistic and mixed probabilistic-deterministic) are presented next.

Fully Probabilistic Risk Assessment

The probability distribution of losses and the LEC that results from the previous activity are used to obtain specific risk measures or metrics as defined by ERN-AL (n.d. a, n.d. f), Cardona et al. (2015) and Ordaz (2000).

- Average annual loss, or AAL: corresponds to the expected value of the annual loss, and as such, it is calculated by integrating the LEC (area under the curve, Equation 66) or directly by computing the expected value of the set of loss events (Equation 6-7). Thus, it is the annualization of the losses that are expected to occur in the future (until eternity and if the hazard process remains stationary) considering all possible events. It is considered a useful metric because of its capacity to synthesize the entire loss generation process in a single number. Insurance schemes use the AAL and refer to it as the "pure premium" (Informa UK, 2008) over which other factors are added to determine an insurance premium.

Equation 6-6 $$AAL = \int_0^\infty \nu(\ell)\, d\ell$$

Equation 6-7 $$AAL = \sum_{i=1}^{n} E[\ell|e_i] \cdot F_{e_i}$$

- $\nu(\ell)$ is the loss exceedance rate of loss ℓ (Equation 6-2), $E[\ell|e_i]$ is the expected value of the loss ℓ for the i^{th} hazard event, (Equation 6-4), and F_{ei} is the annual frequency of occurrence of the i^{th} hazard event, e_i.

- Probable maximum loss, or PML: This metric derives its name from the insurance industry which looks at losses that are very rare, that is, losses that are either very infrequent or have very long return periods. The PML is a specific loss value associated with a long return period (usually the PML is elected as the value for a return period between 200 and 1,500 years, but there is no universal standard that defines it). The return period is simply the inverse of the annual probability of exceedance (Grossi, 2005).

- Loss exceedance probability in a timeframe: Because it is assumed that the hazard occurrence process in time follows a Poisson Process, then the probability of exceeding a loss value within T years can be calculated from the LEC using Equation 6-8. This provides an answer the question: What is the probability that a certain loss value will be exceeded within, for example, 50 years? It is useful to calculate these probabilities for different "exposure" timeframes, which can be related to, for example, the expected lifespan of an infrastructure.

Equation 6-8 $$PE(\ell, T) = 1 - e^{-\nu(\ell)\cdot T}$$

Additional risk metrics, in terms of different probabilities that can be computed, can be calculated thanks to the fully probabilistic framework used. For more details, see Cardona et al. (2015) and Bernal (2014) (e.g., the probability of having N events exceeding loss ℓ within a timeframe T, the probability of exceeding a loss ℓ after the occurrence of an event).

Simplified Probabilistic Risk Assessment

Given the limited probabilistic treatment and calculation of risk within this type of assessment, the complete LEC cannot be obtained, and only the AAL can be calculated given that it is an expected value. To compute the AAL, the hazard curve (containing the rates of exceedance, the inverse of the return period, of different intensity values of the hazard) is used (instead of the individual stochastic hazard events in a fully probabilistic assessment) together with the expected losses for those intensity values (from the vulnerability module) to calculate th'e average annual loss (CIMNE et al., 2013b). Equation 69 shows the equation to calculate the AAL from the hazard curve (CIMNE et al., 2013b)

Equation 6-9 $AAL = \sum_{j=1}^{N} \int_{0}^{\infty} -\frac{1}{v_j(0)} \cdot \frac{dv_j(s)}{ds} \cdot E_j[l|s]\, ds$

where $v_j(s)$ is the hazard curve (hazard intensity exceedance rates) for exposed element j, and $E_j[l|s]$ is the expected value of the loss for a given hazard intensity s.

Usually Equation 6-9 is discretized, where the exceedance probabilities are converted to occurrence probabilities and average losses are calculated between consecutive return periods, and then these are multiplied to obtain the average annual loss (FEMA, n.d.a.). **Equation 610** shows how to calculate the AAL by doing this (FEMA, n.d.a.)

Equation 61-0

$$AAL = v_{TR_m} \cdot L_{TR_m} + \sum_{i=0}^{m-1} \left(v_{TR_{m-i-1}} - v_{TR_{m-i}}\right) \cdot \frac{\left(L_{TR_{m-i-1}} + L_{TR_{m-i}}\right)}{2}$$

where v_{TR_m} is the hazard exceedance rate of a given return period, L_{TR} is the associated loss for a given return period, i is an index going through all the return periods to be used, and m is the largest return period used. This calculation is shown next if the following five return periods are used: 25, 100, 500, 1000, and 2000.

$$AAL = v_{2000} \cdot L_{2000} + \left((v_{1000} - v_{2000}) \cdot \frac{L_{1000} + L_{2000}}{2}\right) + \left((v_{500} - v_{1000}) \cdot \frac{L_{500} + L_{1000}}{2}\right) + \left((v_{100} - v_{500}) \cdot \frac{L_{100} + L_{500}}{2}\right) + \left((v_{25} - v_{100}) \cdot \frac{L_{25} + L_{100}}{2}\right)$$

Mixed Probabilistic-Deterministic Risk Assessment:

Depending on how the risk model was built, certain components would have been treated probabilistically (and within this, fully or simplified) and others deterministically. Following the two cases discussed before (the hazard is estimated probabilistically and the vulnerability deterministically, or the hazard is estimated deterministically and the vulnerability probabilistically) the metrics will vary.

For the first case where the calculation of risk allows for the LEC to be obtained, either directly (if treated as fully probabilistic) or via proxy (if treated as simplified probabilistic), the same metrics described above for these two approaches apply. For the second case where the calculation of risk does not allow for the LEC to be obtained, risk metrics will depend on punctual results and on the specific sector and hazard-specific methods used to calculate risk. Some of the methods such as detailed structural modelling including structural reliability theory (Johansson et al., 2013), finite-elements and Monte Carlo simulations, among others, allow for risk measures such as probability of having certain damage states, probability of failure or damages for varying levels of reliability, for example.

Deterministic Risk Assessment

This approach requires fewer resources than the probabilistic approaches. It is very useful on its own to evaluate extremely complex structures that require a higher level of detail and where a probabilistic approach may be impractical. It can also be used to help the public better understand the hazard since it has occurred in the past and those events may still be remembered. Similar to the probabilistic assessment, two large groups of activities can be identified: the first one includes the building of the three individual modules of hazard, exposure, and vulnerability, and the second one focuses on performing the risk calculations. Within the first group, the three activities it includes are: (1) model hazard event, (2) construct a geodatabase storing all relevant attributes of the exposure, and (3) model structural and social vulnerability. Within the second group, the two remaining activities are: (4) make sure the hazard, exposure, and vulnerability modules are appropriate and have interoperability with each other, and (5) mathematically calculate direct and indirect losses.

1) Model hazard event:

This activity involves constructing a deterministic hazard model for all the hazards that can impact the project by modeling specific hazard events. This activity is explained in detail in the section **Quantification of the hazard component**.

2) Construct an exposure geodatabase:

This activity involves constructing a geo-referenced database of exposed assets (including buildings and infrastructure, as well as population) that gathers all characteristics that are relevant to evaluate vulnerability to natural hazards. This activity is explained in detail in the section **Quantification of the exposure component**.

3) Model structural and social vulnerability:

This activity involves constructing a vulnerability model for all the physical assets that are part of the exposure, as well as of the exposed population. This activity is explained in detail in the section **Quantification of the vulnerability component**.

4) Ensure that individual modules have interoperability:

This activity involves reviewing the completed individual modules and ensuring that there is compatibility and interoperability among them. The following conditions must be met:

- For the hazard module: The outputs of the hazard model that become inputs to the risk model consist of a hazard event spatially (in a GIS format) representing the selected intensity. It needs to have a spatial representation so that the hazard and exposure modules can communicate; this means having GIS layers (typically in a raster format) for the hazard event with a proper georeferentiation and coordinate system compatible with that of the exposure module. For the second characteristic, an appropriate intensity measure must be selected that best correlates with physical damages in order for the hazard and vulnerability modules to communicate; this means expressing the hazard in terms of a measure of intensity that corresponds to the same measure of intensity used by the vulnerability module to determine damage.

- For the exposure module: The output of the exposure module that becomes an input to the risk model consists of a database of all exposed assets and population that has a spatial representation (as it is georeferenced, it is also called a geodatabase) and that stores all relevant physical and social characteristics. The first characteristic refers to the compatibility between the hazard and exposure modules explained above. The second characteristic is needed so that the exposure and vulnerability modules can communicate: it refers to storing the physical structural characteristics (for infrastructure), such as constructive type, structural system, general dimensions, geometry, state, etc., and social characteristics (for exposed population), that directly correspond to the vulnerability relationships contained in the vulnerability module that provides expected damages.

- For the vulnerability module: The outputs of the vulnerability module that become inputs to the risk model consist of a vulnerability relationship that is built for specific physical characteristics, that provides estimated damages as a function of a specific hazard measure of intensity. The first characteristic refers to the compatibility between the vulnerability and exposure modules explained above. The second characteristic refers to the compatibility between the vulnerability and hazard modules explained above.

5) Calculate direct, indirect, and total losses:

In this activity, the three individual modules described above are combined to determine direct, indirect, and total losses. The risk calculation procedure for both types of deterministic risk assessments presented in Table 6.1 (past-historical or worst-case event) is presented next.

Because a deterministic approach by definition does not consider uncertainty, all the model's properties are uniquely given (Ditlevsen and Madsen, 2005). Thus, as stated by the United Nations Office for Disaster Risk Reduction (UNDRR, 2015), "in contrast [to a probabilistic model], a deterministic model treats the probability of an event as finite [;] the deterministic approach typically models scenarios, where the input values are known, and the outcome is observed." This makes the risk calculation straightforward, following this sequence:

i. Superimpose the exposure to the hazard event that was modelled or mapped and determine the resulting hazard intensity experienced at the location of the exposure.

ii. Use this intensity value to enter the vulnerability module (which can be in terms of damage curves or specific structural models) and determine the corresponding damage level.

iii. Relate this damage value (which can be in terms of a damage percentage or a discrete damage state) to a corresponding economic loss and injuries or loss of lives using general damage-loss relationships available in literature or performing a detailed economic evaluation of the damage.

*Robust Decision Making

Because RDM is more of an integrated evaluation of proposed actions and decision making, this approach is detailed in the section on Evaluation and Prioritization of Risk Reduction Measures further down in this chapter. However, because it is a framework of decision making under deep uncertainty, it is flexible in terms of the models it can use to perform the risk assessments themselves. These models (which are used to evaluate the multitude of possibilities) can be in the form of Excel, R or Python-based simulation models, for example, or can use sector-specific modeling platforms. This is where the disaster and climate change risk-specific modeling platforms that have been described and used throughout this Methodology, such as CAPRA and Hazus, can be used as the modeling engine within the RDM framework. All that is needed to complement these simulation models is a "wrapper" to run a multitude of cases. Some examples include the open-source Rhodium python library (see https://github.com/Project-Platypus/Rhodium) and the RAP™ – Robust Adaptive Planning - or CARs™ - Computer Assisted Reasoning – software by Evolving Logic (see https://www.evolvinglogic.com/el_news.html).

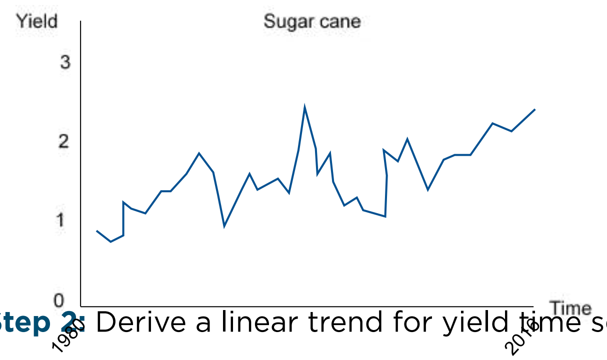
*Historical Timeline Analysis

This type of analysis is a simplified risk assessment method used specifically for the agriculture sector. This method is treated as a special case in this Methodology since more detailed disaster risk models for the agriculture sector are still very new and under development; hence, the other more standardized approaches detailed in this Methodology for risk assessment do not necessarily apply to this sector.

The World Bank (2016) developed this method, which it sets forth in its Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners. This method does not aim to develop hazard, vulnerability, and risk models in depth; instead, it estimates agricultural production losses due to natural hazards using historical loss data. A time series of hazard events (typically only of hydrometeorological hazards) is built from historical records, and at the same time a second timeseries of agricultural production (e.g. yield) is also built for the same window of time. These two time series are then analyzed together to determine possible correlation and causation between the occurrence of a hazard event and a decrease in productivity. The following steps outline the process:

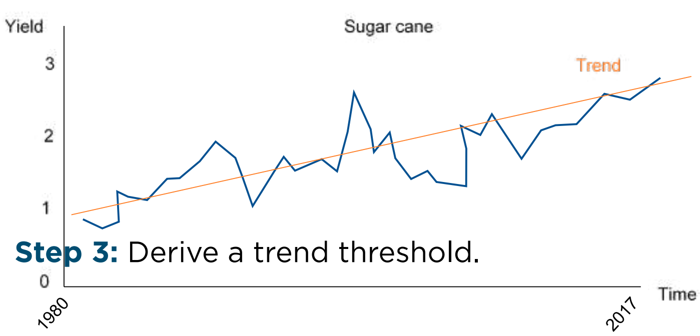
Step 1: Obtain time series data of yields.

For each crop under study, construct a timeline of yield data for as many years as possible, using either country or local data or data from FAOSTAT.



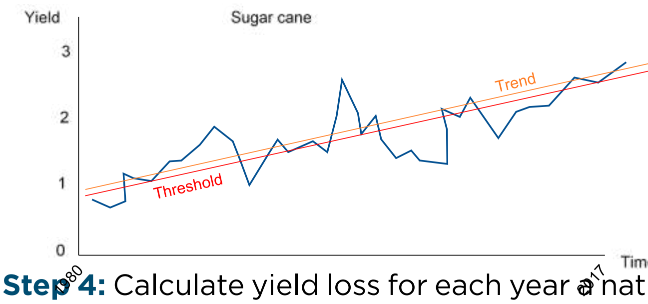
Step 2: Derive a linear trend for yield time series.

Once this time series is constructed, perform a linear regression using ordinary least-squares on the dataset to obtain a linear trend. This historical trend should be extended to project future conditions, and this should represent a scenario without climate change. To consider climate change, adequate climate change evaluations should be carried out to obtain an estimated change in the projected trend into the future.



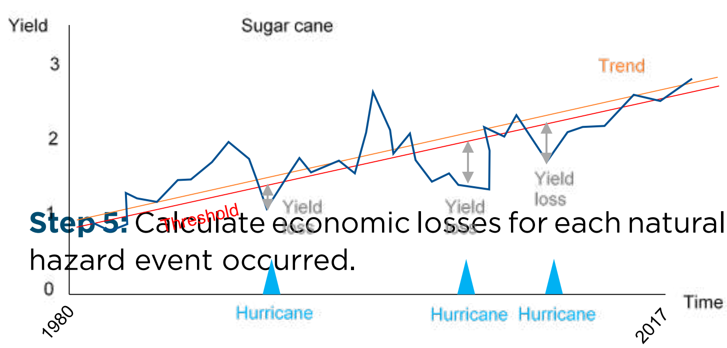
Step 3: Derive a trend threshold.

Using the time series data, calculate the standard deviation and establish a threshold value as one-third of the standard deviation. This threshold value should be subtracted from the linear trend and used to create a threshold linear trend, which represents the normal deviations in the yield that can be expected as part of doing normal business. This is done to consider drops in the expected trend that are not extraordinary.



Step 4: Calculate yield loss for each year a natural hazard event occurred.

From the event timeline, select the natural hazards that have impacted the agriculture sector in the past, and for each of these, match the events on the yield time series constructed in the past steps. For each event that has a corresponding drop in yield below the threshold trend, calculate the drop or loss: the loss is the difference between the threshold linear trend (the expected yield) and the actual yield (from the historical data). Calculate the yield losses for all events that occur in the time series. This should be done separately for each natural hazard, so that in the end the yield losses should be separated for each crop and each hazard.



Step 5: Calculate economic losses for each natural hazard event occurred.

To obtain economic losses for each event, the yield losses determined in the previous step should first be multiplied by the total harvest for each crop (to obtain output losses) and then by its price. To obtain the price for each commodity, use yearly prices and convert them from nominal to constant value.

Step 6: Calculate the average annual loss.

For each crop and each hazard, first add all of the economic losses obtained in the previous step (individual losses for each event), which will give a total loss over the window of time considered, and then divide this total loss by the timeframe to obtain an AAL. Hence, an AAL will be obtained for each crop and for each hazard. AALs from all the hazards can be added to get the multi-hazard AAL for each crop.

After obtaining AAL for each hazard and for each crop, the different risk levels for different crops should be determined to be able to identify the most critical crops (highest risk, i.e., highest AAL), and the least critical (lowest risk or AAL).

***Exposure Assessment**

Although this is not a risk assessment, this analysis can work as a simplified quantitative assessment for those cases that are less complex and do not carry grave concerns of project viability or risk exacerbation, and thus do not require a risk assessment, and where there are serious limitations of time, resources, and data. This analysis, which lacks the vulnerability component, involves overlapping the hazard and exposure modules to analyze what is exposed to the hazard(s) in terms of quantity and types of infrastructures, overall exposure values, geographic distribution, and others. This does not provide risk results: economic losses or loss of life. This type of assessment is compatible with a hazard susceptibility assessment (see Section 6.1.4.2, **Quantification of the hazard component**).

The following sections (6.1.4.2, 6.1.4.3, and 6.1.4.4) detail how to build the components of the risk model (hazard, exposure, and vulnerability) for each risk assessment approach described above.

6.1.4.2 Quantification of the hazard component

Quantification of the hazard is the first step in the disaster and climate change risk assessment process, and it aims to more precisely assess where and how each natural hazard could occur. This means, in general and for all hazards, studying a hazard's **spatial extent**, **intensity,** and **frequency**.

Given that natural hazards are innately spatial, the spatial extent refers to the geographic distribution of the possible events. This is why hazards are commonly expressed through maps. However, care should be taken when interpreting maps considering, first, that hazard maps only show one building block of risk (hazard maps are sometimes mistakenly referred to as risk maps), and second, that maps show only a snapshot of the other two characteristics of hazards: intensity and frequency.

Intensity is the measure of a hazard's strength. Different hazards have different intensity units in an attempt to arrive at a common way to quantify its strength. For example, the intensity of seismic hazard is measured by ground motion, usually peak ground acceleration, and the intensity of flooding hazard is measured by water depth and water velocity. Frequency refers to the recurrence rates of events of different intensities, that is, how often small, medium, and large events occur.

6.1.4.2.1 General hazard assessment considerations

Various methods exist to evaluate a hazard through its three components - **spatial extent**, **intensity** and **frequency.** This section will provide guidance on selecting the optimal hazard assessment approach, including integrating climate change into the hazard assessment, for different hazards. Table 6.3 summarizes the three basic kinds of hazard assessments.

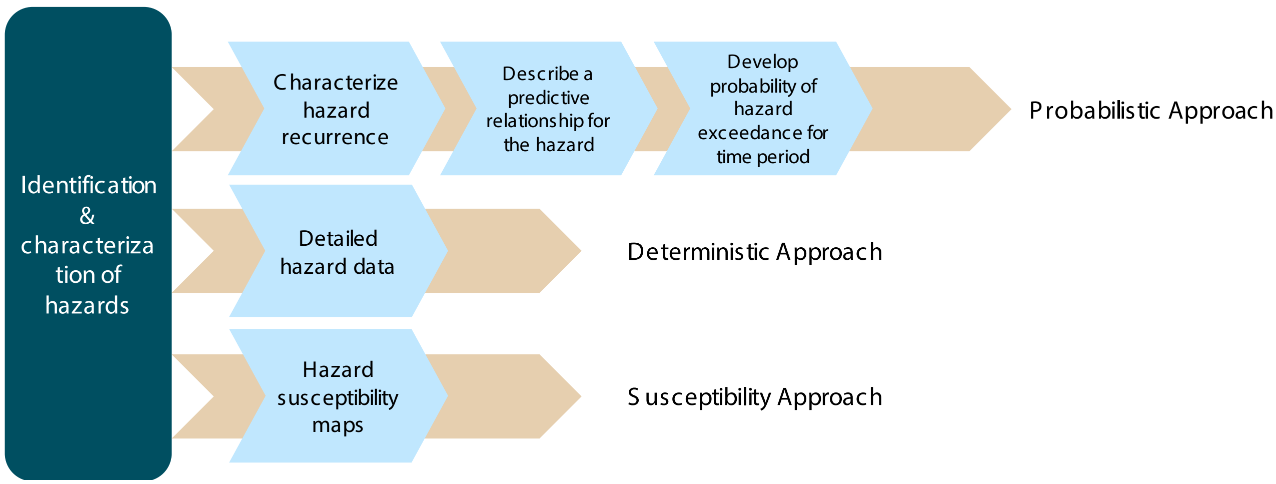
Table 6.3. Hazard Assessment Approaches

Method	Description	
Probabilistic hazard assessment	In a probabilistic hazard assessment, the hazard is represented through a stochastically generated set of mutually exclusive and collectively exhaustive events that could occur, each associated with a frequency of occurrence (which should be modified to accommodate climate change effects). In this way, the model is able to statistically represent the probability of all possible events (even those that have not yet occurred) and the modifications due to climate change. The hazard output consists of an extent and intensity associated with a likelihood. The return period is usually used to describe a probabilistic hazard product; the return period is the inverse of the annual frequency of exceedance. To conduct a probabilistic risk assessment, a probabilistic hazard assessment must be used.	Fully probabilistic assessment: Scientific models are used to simulate the physical processes that generate hazards (e.g., faults that generate earthquakes or river hydrology—hydraulics that generate flooding). Tens, hundreds, or thousands of individual stochastic events must be generated, each one describing a unique way in which the hazard may present itself (in terms of location, strength, and recurrence). These events are used to calculate risk (note that the probabilistic aggregation of these results in integrated hazard maps with associated return periods; however, these are only used to convey hazard results). Because individual events are used, subsequent risk calculations are fully probabilistic and thus the LEC, AAL and PML are obtained.
		Simplified probabilistic assessment: This approach can be used when modeling individual events stochastically is not practical (due to time or resource constraints) or integrated hazard maps with different return periods (integrated hazard refers to the end result of having mathematically combined the contribution of different events) already exist. In this case, the values of hazard intensity are read from the integrated hazard maps to recreate a hazard curve for the location of interest. Usually, five or more return periods are required for an adequate analysis (to consider both rare-large and recurrent-small intensities). This allows for the direct calculation of the AAL and an estimation via extrapolation of the LEC in a subsequent risk calculation.
Deterministic hazard assessment	In a deterministic hazard assessment specific individual events are taken as representative of the hazard. In contrast to a probabilistic model, one or a few events are evaluated to determine the specific impact of these. Typical deterministic scenarios include evaluating historical events or worst-case scenarios. It should be acknowledged that under climate change, loss of stationarity might generate threats of new types and larger events. This approach may be used in conjunction with a probabilistic model to validate/ calibrate.	Past historical event: Hazard data may exist for a single past event, which could be modeled if the extent and intensities are known. This approach can also be used to help the public better understand the hazard since it has occurred and may be remembered. The hazard output consists of an extent and magnitude associated with a specific event.
		Worst-case event: An event representing extreme conditions (worst-case) could be modeled using appropriate software for events that have not occurred. Events analyzing future conditions must be modeled since they have not occurred in the past. The hazard output consists of an extent and magnitude associated with a specific modeled event.
Susceptibility hazard assessment	This analysis involves creating a map showing areas where there is more susceptibility to a particular hazard. In some cases, these maps are created using base variables (e.g., landslide susceptibility may be generated using slope, land cover, and soils). Some hazards are difficult to model probabilistically or deterministically, and a susceptibility map is all that is needed to identify the hazard. Once the map is created, it is overlaid with the assets to perform an exposure assessment (this approach does not support a risk assessment).	
*Historical timeline[21]	This approach applies only for the agriculture sector for which detailed risk assessment methods are not very common, as the current state of the art is still in development. This risk approach builds a timeseries of historical events (mainly of hydrometeorological hazards) and a parallel time series of agricultural production and attempts to establish causation between the two and estimate average annual losses from this. The hazard component thus consists of building a timeline of historic events.	

21 This type of analysis is a simplified risk assessment method used specifically for the agriculture sector. This method is treated as a special case in this Methodology given that more detailed disaster risk models for the agricultural sector are still very new and under development; hence, the other more standardized approaches detailed in this Methodology for the hazard, exposure and vulnerability components do not necessarily always apply to this sector.

The activities that comprise each of the three approaches (probabilistic, deterministic, and susceptibility) are summarized in the flow chart below.

Figure 6.7. Summary of Activities to Develop a Hazard Assessment



Probabilistic Hazard Assessment

This type of assessment provides a user with more information on the geographic area that could be impacted, the potential severity of the impacts, and the likelihood of occurrence. It is the most resource intensive of the three approaches. Four activities have been identified for the probabilistic analysis approach: (1) identification and gathering of hazard data, (2) characterization of hazard recurrence, (3) description of a predictive intensity relationship for the hazard, and (4) development of the hazard curve.

1) Identify and gather hazard data

This activity involves identifying and gathering all the data that will be used to assess the hazards that may impact the project site. A record of how often these events occur must also be developed or collected. The following questions should be used to help determine which of the two above-mentioned approaches within a probabilistic hazard assessment should be used:

- Are there software models and data inputs available to generate a fully probabilistic model? If so, collect them and move to Activity 2 with a fully probabilistic approach. If the data do not exist, move to a simplified probabilistic approach and continue with the next question.
- Is there an existing and available probabilistic assessment expressed through integrated hazard maps for at least five return periods? If so, collect it in a GIS format and move to Activity 2 with a simplified probabilistic approach. If the data do not exist, move to a deterministic approach.

2) Characterize hazard recurrence:

This activity involves characterizing the temporal distribution of the hazard event recurrence. This recurrence relationship specifies the average rate at which a hazard event will be exceeded. The following bullet points are meant to help guide the process.

- For the fully probabilistic approach, model the temporal uncertainty. This activity begins by assuming that the occurrence in time of hazard events follows a Poisson process (a continuous stochastic process of occurrence of discrete events where the average time between events is known but the exact timing of events is random, and all events are independent, that is, the process has no memory), and continues to develop an event recurrence relationship to obtain a stochastic mechanism for the generation of hazard events. Specific ways to model event recurrence exist for each hazard. Use the hazard-specific guidance given further down in this chapter and the computer models described in Appendix D to generate the data and the temporal uncertainty.

- For the simplified probabilistic approach, use the hazard's return period as the representation of the hazard recurrence. Use the hazard-specific guidance provided further down in this chapter.

3) Describe a predictive intensity relationship for the hazard:

The hazard intensity parameters produced at the project site for different size events must be determined using predictive relationships. The following bullet points are meant to help guide the process.

- For the fully probabilistic approach, model the intensity predictive relationship using hazard-specific models. This activity involves combining the previous activity of characterizing event recurrence and using an intensity relationship to predict the probability of getting various intensities. The measure of intensity is modeled as a random variable defined by its first two statistical moments. Use the hazard-specific guidance given further down in this chapter and the computer models described in Appendix D to generate the predictive relationships. If the expertise and data requirements are available, create the data in an electronic format.

- For the simplified probabilistic approach, use the resulting hazard intensities coming from either detailed hazard-specific models or integrated hazard maps. Use the hazard-specific guidance given further down in this chapter.

4) Develop probability of hazard exceedance for specific time periods:

In this activity, the uncertainties associated with location, magnitude, and hazard parameter prediction are combined to determine the probability at which a specific hazard intensity will be exceeded during a particular period. The following bullet points are meant to help guide the process.

- For the fully probabilistic approach, model the hazard exceedance for specific time periods. This activity involves applying hazard-appropriate probability distributions and developing hazard curves for the project site(s). Use the hazard-specific guidance given further down in this chapter and the computer models described in Appendix D to generate the hazard curves.

- For the simplified probabilistic approach, plot the resulting hazard intensities and their corresponding return periods to build the hazard curve.

Deterministic Hazard Assessment

This approach may be used in conjunction with the probabilistic analysis to validate and calibrate the modeling. It can also be used to help the public better understand the hazard since it has occurred in the past and may be remembered. To conduct a deterministic analysis, two activities have been identified: (1) identify and characterize hazards and (2) develop detailed hazard data.

1) Identify and gather hazard data:

This activity involves identifying and gathering data on the specific event to be modeled. The following questions should be used to help determine which of the two above-mentioned approaches within a DHA should be used:

- Is there data available to model a past or worst-case event? If so, collect it and move onto Activity 2. If the event data does not exist, move to a simpler mapping of a past event approach and continue to the next question.

- Is there existing anecdotical data available for a past event? If so, collect it and generate GIS format hazard maps and move onto Activity 2. If the data does not exist, move to a susceptibility approach.

2) Model the hazard event:

This activity involves using the procedure identified in the previous activity to model and map the hazard to be assessed. The hazard intensity parameters produced at the project site for the selected past or worst-case event must be determined using predictive relationships. The following bullet points are meant to help guide the process.

- For the modeling approach, model the predictive relationship. This activity involves using detailed data and physically and mathematically based models to recreate the event. Use the hazard-specific guidance given further down in this chapter and the computer models described in Appendix D to generate the hazard representation for the event.

- For the mapping past-event approach, directly map extents and intensity values. This activity involves using readily available data on spatial extent and intensity values to map the event. Use the hazard-specific guidance given further down in this chapter to generate the hazard map for the event.

Susceptibility Hazard Assessment

This analysis involves creating a map showing areas where there is more susceptibility to a particular hazard. Some hazards are difficult to model probabilistically, and sometimes a susceptibility map is useful to identify the hazard. This approach is simpler and not as resource-intensive as the other ones.

1) Identify and gather hazard data:

This activity involves identifying datasets to be used as variables to determine areas of different hazard levels. The following questions should be used to help determine an approach depending on the data available:

- Are there data available to create a susceptibility map? Other sources of information may be used to help map and generate a hazard susceptibility layer. This analysis should be conducted in a GIS and the outputs collected. If so, move on to Activity 2. If not, continue to the following question.

- Are there susceptibility maps available? If so, collect them in a GIS format and move onto to Activity 2.

2) Develop susceptibility maps:

This activity involves using the procedure identified in the previous activity to map the hazard susceptibility. These output datasets usually include a polygon map with ranked areas. Use the hazard-specific guidance given further down in this chapter to create the maps. The output is meant to be easier to generate than a probabilistic or deterministic analysis and to give the user a general sense of what may be impacted by the hazard. Use the hazard-specific guidance given further down in this chapter.

*Historical Timeline Analysis

This type of analysis is a simplified risk assessment method used specifically for the agriculture sector. This method is treated as a special case in this Methodology given that more detailed disaster risk models for the agriculture sector are still very new and under development; hence, the other more standardized approaches detailed in this Methodology for the hazard, exposure, and vulnerability components do not necessarily apply for this sector.

The World Bank (2016) developed this method in its Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners. This method does not seek to develop hazard or vulnerability models in depth; instead, it estimates agricultural production losses due to natural hazards using historical loss data. Hence, within this risk approach, the hazard component is treated implicitly through the construction of a timeline of past events. This timeline of past natural hazard events (mainly hydrometeorological hazards, since these have an impact on crops) shall be constructed for the longest time period possible (and it should be the same window of time as the agricultural production timeline to be built), and shall include events of flooding, drought, extreme temperature changes, and hurricanes (considering both storm surge or wind effects). This timeline may be differentiated by type of hazard to determine average annual losses per hazard. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section for details on the risk calculation.

6.1.4.2.2 General climate change considerations

Climate change considerations are relevant to most, but not all, types of hazards. The details of the approach depend on how potential climate change can influence the hazard. They also depend on which Hazard Assessment Methodology is selected (Table 6.3), which can range from a simple assessment of susceptibility to a detailed probabilistic analysis with complex modeling tools. The flow chart below presents the climate assessment approach beginning with general consideration activities and moving on to hazard-specific activities.

Figure 6.5. General Considerations in Choosing a Hazard-Specific Approach

General Considerations

Climate change effects add another level of uncertainty to the hazard analysis. The evolution of future climate conditions, which depends on human activities such as future greenhouse gas emissions, cannot be predicted with certainty; different climate models provide divergent projections of relevant climate responses even when forced by the same assumptions.

The direction of change in temperature is generally highly robust (i.e., warming), and spatial differences are fairly small. For precipitation, however, the model-to-model differences are expected to be greater, and the response fields at the grid point level are commonly much noisier. It is therefore important to assess the large-scale patterns of change and to see if the change fields exhibits broad, dynamically related structures or if the projections are dominated by grid-point noise and natural variability. It is also useful to compare the projected changes with the underlying, inherent variability (variance or standard deviation). For many places on Earth, large natural variability renders many projected changes in mean rainfall as only marginally significant or non-significant, particularly over the next several decades. But the very small natural variability in the low latitudes generates the opposite problem: even small projected changes can quickly lead certain quantities to fall outside of the previously experienced range, and the chance for substantial impacts in the environment can therefore potentially be rather high.

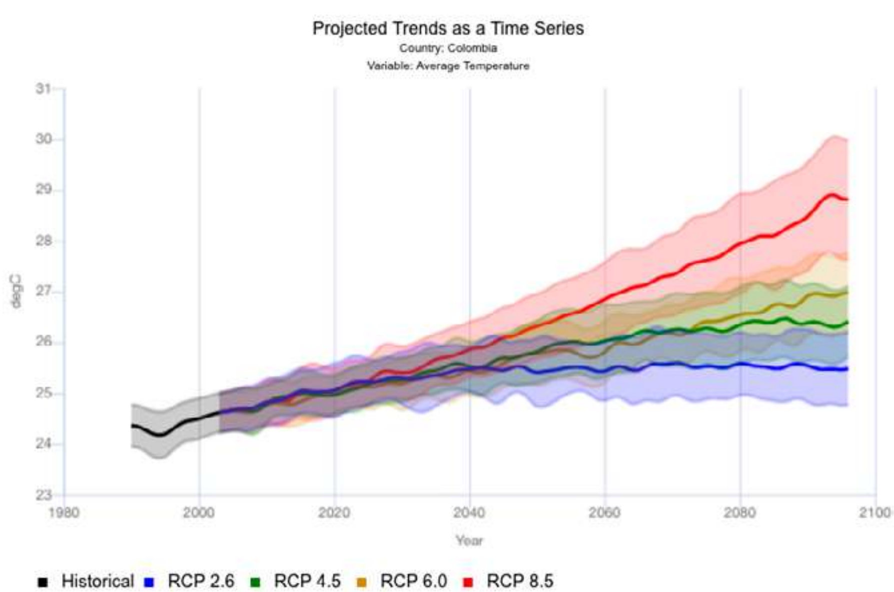
Hazard assessments typically focus on extreme events. Thus it is not sufficient to examine only the mean values of model projections of future climate. Hence, it is also interesting to consult projected changes in year-to year fluctuations (variability) or even in the tails of the distribution (more extreme conditions) of daily or monthly climate characteristics (e.g., highest precipitation intensities). While the means might show little change relative to the natural variability, the extremes might respond much more substantially. Often, this response can be tied back to the warming atmosphere, which provides a higher potential capacity to transport moisture, making more water available for rain (Clausius-Clapeyron relationship). Higher extremes are therefore also possible in regions where the mean rainfall might be projected to decrease. However, the model-to-model differences in this quantity might also be fairly large, making it important to consult the quality of the models. Overall, global climate models with greater than 100 km resolution are not the ideal tools to study small-scale extremes, although they point out the potential for changes that can have significant impact on the ground.

One approach that may be taken is to evaluate multiple available general calculation models (GCMs) and choose models that define reasonable maximum probable hazard under climate change (e.g., models near the 90th percentile of the distribution relative to the hazard of interest). Another approach is to use a multi-model ensemble mean as the most likely future outcome, then examine differences over the ensemble of models to help inform the uncertainty in this estimate.

Generally, when consulting model projections, and because future climate is uncertain, it is not advisable to rely on the output of a single climate model to assess climate change risk. Instead, it is important to try to capture the range of reasonably likely climate conditions as they relate to hazards of interest. Moreover, it is helpful to consider large ensembles of model outcomes, as individual models might exhibit various forms of bias. A multi-model ensemble of 10 or more models tends to be quite robust. However, the multi-model mean also tends to hide the range of uncertainty that is given by the span of results across the different models. Therefore, having access to individual models can be useful. Other metrics of model spread, such as percentiles across an ensemble, also help to represent the range of uncertainty.

Finally, a consultation of multi-model time series of change can be particularly useful for more clearly separating the different assumptions of emission scenario, model uncertainty, and timing of change vis-à-vis an observed reference series (Figure 6.6 shows the CMIP5 multi-model projections of country-aggregated temperature change for Colombia following different RCPs). The individual series have been smoothed with a seven-point filter to suppress noise from year-to-year variability. Note the overlap of RCPs up to about 2040 and subsequent separation of the warming signal. The shaded range indicates the 10th to 90th percentile across the multi-model ensemble results.

Figure 6.6. Example of Climate Change Projections



Despite continuing improvements in GCMs and computational capabilities of high-performance computers, the spatial resolution of the current suite of GCMs is still too coarse for direct use in project-specific applications. For example, the spatial resolution of the GCMs included in the most recent Coupled Model Inter-comparison Project Phase 5 (CMIP5) ranged from approximately 0.5 degree to 4 degrees in horizonal (approximately 50 km to 400 km) (Taylor et al., 2012). To overcome a resolution issue, downscaling is a common approach for translating the climate change signals represented by climate models to changes in meteorological parameters at the regional and local scales.

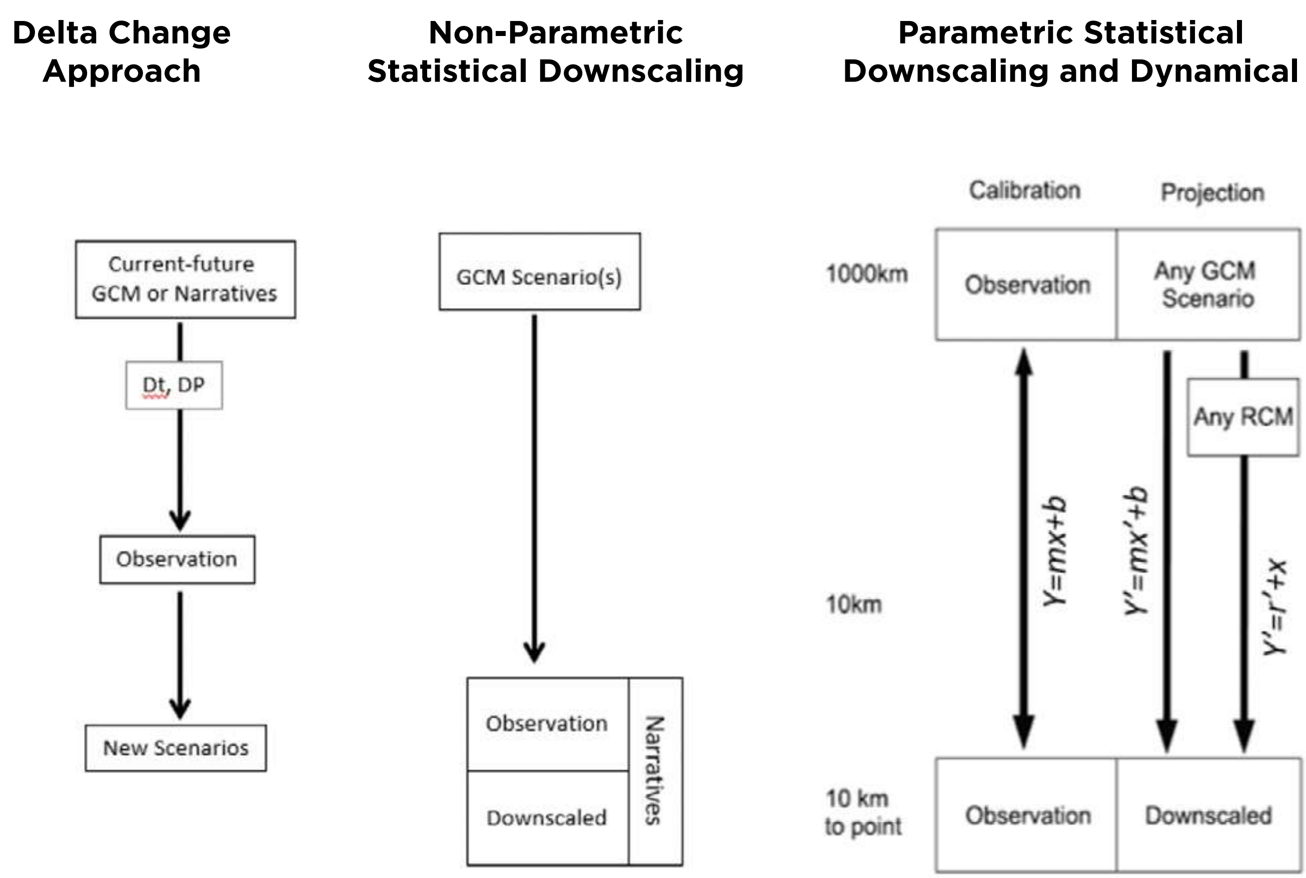
GCM output that has been spatially downscaled and bias-corrected can help address the scale issue, but only in areas where extensive local climatic records are available to support the downscaling and bias correction process. A range of different downscaling approaches have been developed, ranging from simple delta approaches, whereby the historical meteorological record is simply incrementally adjusted, to more sophisticated statistical methods that relate large-scale atmospheric processes to local scale observations.

Multiple downscaling approaches exist for translating coarse resolution climate model outputs to the local scale, with two broad categories generally considered, including (i) statistical downscaling, which develops mathematical relationships between observed climate fields and large-scale and/or small climate model outputs, and (ii) dynamical downscaling, which makes use of physically based regional climate models (RCMs). In statistical downscaling, mathematical relationships between observed meteorological parameters at various locations are related to broader-scale climate parameters at the GCM scale. The relationships, based on historical observations, become a mapping function for use in transferring projected climate conditions from the large scale of the GCM to the local scale of the observations. Statistical downscaling methods often make use of stochastic weather generators that include rigorous stochastic and statistical algorithms (Flint, 2012; Landman et al., 2001; Wilby et al., 2003; Wilby and Dawson, 2013; Yates et al., 2003). An advantage of statistical downscaling methods is that they are computationally inexpensive, while a drawback is the basic assumption that the statistical relationships developed for the historical period also holds for future conditions, which is not verifiable.

Dynamical downscaling involves the use of an RCM to translate the coarse-scale GCM climate fields to the regional or local scale (Mearns et al., 2009; Rasmussen et al. 2016). Regional climate models use the GCM output as boundary conditions to simulate regional/local meteorological processes. Like GCMs, RCMs are based on the explicit representations of the laws of thermodynamics and fluid mechanics, thus dynamical downscaling generally represents high-resolution climate fields such as precipitation with greater accuracy. Dynamical downscaling has not been widely applied, primarily because of its high computing requirements for long-term climate projections. In addition to the statistical and dynamical downscaling methods, there are hybrid methods that combine both approaches.

Figure 6.7 summarizes these commonly applied methods used in downscaling GCM results for infrastructure planning and hazards analysis. The simplest approach is often referred to as the delta method, where the difference between climate model projections for current and future conditions are taken as an estimate of the relative change of a climate field. For example, the incremental change in temperature is applied to the historic temperature series. The delta method is arguably more appropriate, for example, to water management problems such as drought or reservoir planning, where the temporal resolution of the analysis might be at the monthly level or longer. The delta method may not be appropriate for hazard risk analysis where more temporally refined data are necessary, such as hourly or daily precipitation. Simply shifting precipitation relative to the historic period might not reflect changes in its extreme characteristics such as intensity, frequency, and duration. Other statistical downscaling methods include non-parametric approaches, which make use of classic bootstrapping techniques that resample the historic data to generate new sequences informed by the change signals of the GCMs. The term "non-parametric" refers to the fact that there are no underlying statistical relationships developed; rather, these methods effectively 'reshuffle' the historical data to generate synthetic weather data. A well-known non-parametric method is known as the K-Nearest Neighbor (Rajagopalan and Lall, 1999; Sharif and Burn, 2006; Yates et al., 2003). Parametric methods explicitly develop mathematical relationships between large-scale climate fields and local meteorological observations. The simplest form would be linear regression, where the parameters would be the slope and intercept that form the basis of the relationship between the large-scale climate field and the local observation. Dynamical downscaling is included within the parametric domain of Figure 6.7, since RCMs also translate GCM signals to the local level but do so using a full-fledged atmospheric model. Even then, the results from the RCM runs might not accurately represent local-scale meteorological attributes and would themselves require a statistical transformation (Liu et al., 2017).

Figure 6.7. Summary of Downscaling Methods that Can Be Used to Develop Future Projections



Source: Adapted from Maraun et al. (2010).

Certain activities and questions apply to all types of hazards. In general, assembly of climate-related data can begin by addressing the following questions:

1. Are there previous studies that provide the requisite climate change data, their evaluation, and synthesis regarding suitability for the study?

2. What time horizon is required for the evaluation?

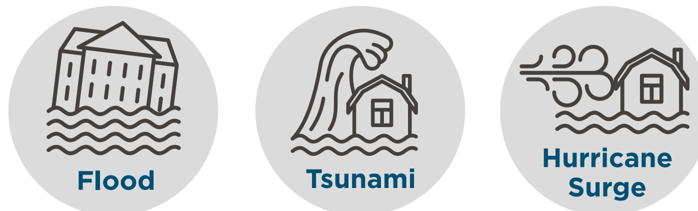
3. If previous studies are not available, what level of detail would be needed and at what spatial and temporal resolution to consider climate change in the disaster and climate change risk assessment?

4. Is a "reasonable" estimate of likely percentage changes sufficient, or are more precise and localized quantitative estimates needed?

The answer to question 4 may require iteration through the steps of the risk assessment to determine whether it makes a difference. Will small changes in the inputs produce large changes in the estimates of risk? If imprecision in the inputs has little impact on risk (either because it does not produce large changes in the hazard or because the level of vulnerability is low), then it makes little sense to pursue a high level of effort to increase the precision of the inputs.

Given the different hazard assessment approaches described above, the specific requirements by hazard are discussed next. Annex D contains more information on the software available for each hazard. When following the methods described here, note that the lack of sufficiently long and good quality observational data can be a strong limitation that hinders formulating design specifications or recognizing the need for changes. Short local records of climate data, for example, often carry the danger of not capturing the inherent natural variability of a place, which leads to underestimation of the local disaster risks as well as misinterpretation of projected future climate changes. There are global datasets that can be consulted, but depending on applications they might not necessarily be sufficient.

6.1.4.2.3. Coastal flooding, tsunami, and hurricane surge



Coastal flooding, also called tidal flooding or shallow coastal flooding, refers to flooding of land adjacent to the shoreline due to sea levels above the normal tidal range. Coastal flooding results from elevated sea levels driven by tsunamis and/or storm surges. When these elevated sea levels hit land, depending on the physical-environmental characteristics that control its impact, it most often leads to flooding of the surrounding coastal area (Benavente et al., 2006).

Storm surges are defined as the inland vertical rise of water above the normal tidal range that occurs when strong winds and low pressure associated with extreme rainfall events, tropical storms and/or hurricanes raise the sea level and form waves that drive water onshore (Kurian et al., 2009). The wave run-up generated by storm surges is defined as the maximum additional height that broken waves attain as they are driven inland before their energy is dissipated (Ebersole et al., 2010).

Tsunamis are another major driver of coastal flooding. They are caused by abrupt disturbances in the sea floor surface generated mainly by earthquakes and, to a lesser extent, major landslides and volcanic activity. Local seismic faults typically generate local tsunamis, affecting the area within minutes of the event (Katsetsiadou et al., 2016). Major seismic events generated in distant faults may create tsunamis thousands of kilometers away. For example, sea floor disturbances in the Ring of Fire in the Pacific Ocean have the potential to generate tsunamis anywhere from Asia to America and are therefore of special importance to the entire Pacific coast of Latin America and the Caribbean (LAC).

Coastal flood events associated with tsunamis and storm surges are responsible for the most deaths and economic damage caused by natural hazards. One of the most damaging events recorded in history was the Bhola cyclone that hit Bangladesh in 1970, generating a 10 m high storm surge that killed as many as 500,000 people (Frank and Husain, 1971). More recently, the 2004 Sumatra–Andaman earthquake off the northwest coast of Sumatra, Indonesia, generated a series of tsunami waves up to 30 meters high, killing an estimated 227,898 people in 14 countries (Satake and Atwater, 2007).

Coastal flood disaster mitigation should be based on a thorough assessment of flood risk. This requires an estimation of the flood hazard (i.e., storm surge or tsunami wave run-up and their associated probability) and the consequences of flooding for the environment, property, livelihoods, and people (Moftakhari et al., 2019). Following is a description of the three dimensions of a coastal flood hazard analysis: extent, intensity, and frequency, as well as the models typically applied to assess this hazard.

Coastal Flooding Hazard Analysis

The extent, intensity, and frequency of coastal flooding hazards are measured by and depend on a range of physical-environmental factors.

- *Extent:* The spatial extent of coastal flooding is generally found by matching the maximum elevation of coastal flood waters with the corresponding topographic contour line elevation inland (Moftakhari et al., 2019).

- *Intensity:* While the fundamental parameter used to estimate the intensity of coastal flooding is the maximum water inundation height, depending on the driver of coastal flooding, additional measures of intensity may be used (Brenden et al., 2018). For coastal flooding driven by storm surge, wave run-up and wave set-up are additional measures used to estimate intensity. For coastal flooding caused by tsunamis, because this hazard can generate two types of sub-hazards—tsunami inundation (slow rising of water) and tsunami flow (torrential flow generating significant lateral forces)—flow velocity (m/s) and momentum flux(m^3/s^2), defined as water flow velocity squared multiplied by water depth, can also be used to estimate intensity.

- *Frequency:* The frequency of coastal flooding is indicated by a defined return period which is an average of how often these events can occur. Coastal floods with small intensities generally occur very frequently while those with large intensities occur very rarely. Usually, engineers use flood water height values with large, specific return periods to design infrastructure able to withstand a wide range of flooding events. Additionally, a hazard curve—a plot of intensity (e.g., water height, water run-up, or flow speed) versus annual rate of exceedance—is used in fully probabilistic assessments to represent the resulting intensity levels considering all possible return periods for flooding events in a particular area (Brenden et al., 2018).

There are a range of physical-environmental controls of the extent, intensity, and frequency of coastal flood hazards. Factors that control the intensity and extent of coastal flood hazards include the geometry of the nearshore and coastal plain, as the lower the slope angle, the more prone to coastal flooding hazards an area may be. Geological composition is also a controlling factor, as coastal areas that have been heavily eroded—where local sea level rise, strong and prolonged wave action, and/or periodic coastal flooding wear down or carry away geological material along the shoreline—also tend to be more susceptible to coastal flooding hazards. This is why rocky coasts dominated by rough material tend to be less vulnerable to erosion and have high capacity to attenuate wave energy, restricting the inland extent of wave run-up (Felton and Crook, 2006). Coastal plains without mangroves, coral reef, sea grasses, or other natural or built barriers are more exposed to tsunamis and storm surge, as they are bereft of coastal protection ecosystem services (Temmerman et al., 2013). Global sea level rise induced by climate change as well as localized land subsidence can amplify the extent and intensity of coastal flooding impacts as it increases the level of the sea relative to coastal land levels. Climate change can also increase the frequency of these events as attendant increases in sea level and temperature make rainfall events, storms and, as a result, storm surge more frequent and intense (Brenden et al., 2018).

The frequency, extent, and intensity of coastal flooding hazards may be estimated and analyzed using approaches that range from the application of simple, basic tools for high-level assessments to highly complex models for detailed analysis.

Commonly Used Tools for High Level Assessments of Coastal Flood Hazards

For storm surge-induced coastal flooding, tools widely used in industry include:

- NOAA's Real-time Coastal Inundation Dashboard (NOAA, n.d.b.): This GIS-hosted portal provides real-time information on tides for a few stations in the Caribbean and active tropical systems, including storm path tracking and intensity forecasting as well as issuing of warnings and watches for at-risk populations. The platform is freely available at https://tidesandcurrents.noaa.gov/inundationdb/

- NOAA's Inundation Analysis Tool (NOAA, s.d.): This tool provides statistics on the frequency and duration of coastal inundations at a given location using observed data from the tide stations of the NOAA Center for Operational Oceanographic Products and Services. The tool is freely available at https://tidesandcurrents.noaa.gov/inundation/

For coastal flooding hazards driven by tsunamis, useful resources for quick, high-level assessments include:

- NOAA's Center for Tsunami Research: Hub for information and further resources available at https://nctr.pmel.noaa.gov/

- NOAA's Deep-Ocean Assessment and Reporting of Tsunamis, DART (PMEL, n.d.): Real-time tsunami monitoring system developed by the Pacific Marine Environmental Laboratory based on monitoring stations positioned at strategic locations throughout the ocean. https://nctr.pmel.noaa.gov/Dart/

- NGDC's (National Geophysical Data Center) Global Historical Tsunami Database: Provides information on tsunami events from 2000 B.C. to the present in the Atlantic, Indian, and Pacific Oceans, as well as in the Mediterranean and Caribbean Seas. Free and open access to the database is available at https://www.ngdc.noaa.gov/hazard/tsu_db.shtml

Commonly Used Coastal Flood Hazard Modelling Approaches

There are several kinds of models that can be run separately or coupled. There are open ocean models and shallow water models, which use different assumptions for the momentum equation. The shallow water models assume that the horizontal scale is much greater than the vertical scale.

There are also different types of flood and surge models. Some models target the hydrodynamics themselves (tidal range and currents), some compute the flooding in nearby dry cells, some are focused on wave propagation from deep and intermediate waters to shallow water, and some focus on wave transformation and interaction with structures (run-up and overtopping models). Some models have modules for each process and often allow coupling between them to get more accurate results. Appendix D provides specific examples of each of these models and the software. The models described in Appendix D are peer-reviewed and have been found acceptable by several government entities.

The two basic data inputs for coastal hydrodynamic models include bathymetry and boundary conditions. Model results can be limited by the bathymetric grid resolution as the higher the resolution the better. Boundary conditions, such as the water level time series, tidal harmonics constituents, river discharges, and wind and currents are also vital data inputs. While bathymetry is fundamental data input for wave models, one can use different combinations of the boundary conditions mentioned, but it is important to represent the most relevant processes in the study area. This kind of model requires the boundary to be a time series of wave parameters (significant wave height, peak period, direction, wave spreading) or wave spectra (energy for each frequency and direction). It can also be a time series of wind if the model has the wind growth option for wave propagation.

For the specific case of storm surge, in addition to the coastal hydrodynamic model, a tropical storm or hurricane model must be used as the generating core of storm surge events.

Probabilistic, deterministic, and susceptibility assessments are the three modelling approaches most commonly used to estimate flood hazards in the coastal region (Moftakhari et al., 2019). Below is an explanation of the basic types of each hazard assessment approach along with descriptions of cases and situations where these models are best applied.

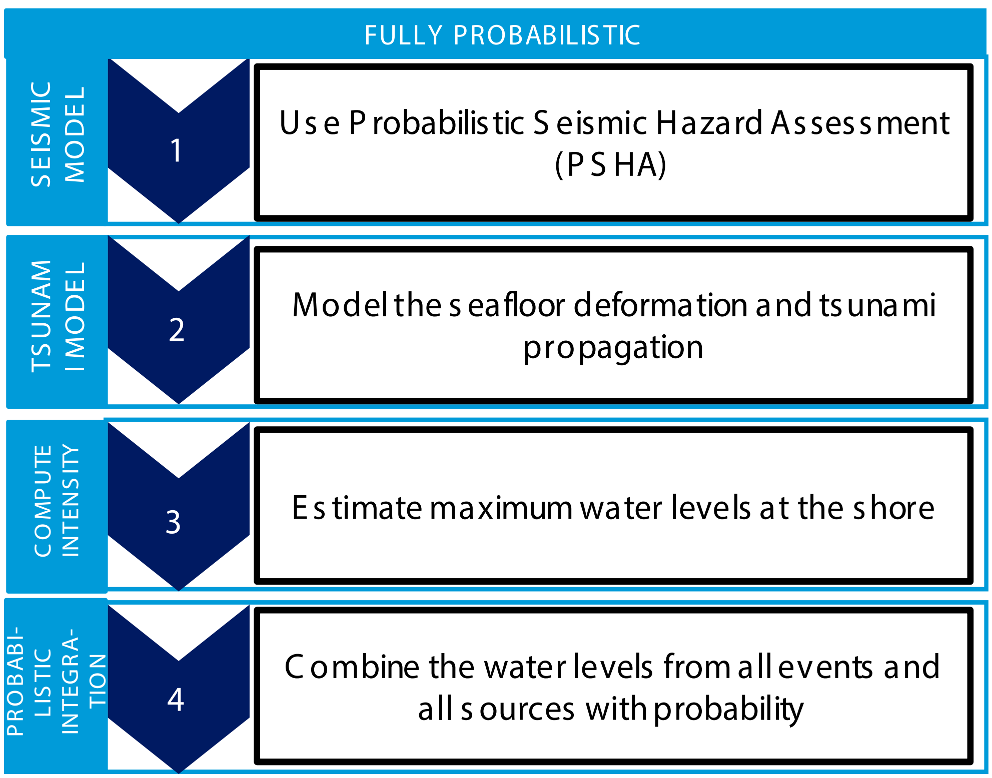
Probabilistic Hazard Assessment: The flood and surge models described above may be difficult to implement to their full extent in a probabilistic framework due to their own complexities, especially if a higher level of detail is required which will in turn require using the most detailed and complex model. If this is the case, then a deterministic model may be better suited, which although it may sacrifice quantifying uncertainties and probabilities of occurrence, it will capture all the highly detailed specifications and requirements. However, unlike deterministic modelling, a probabilistic analysis is commonly used when there are many uncertainties in coastal flood hazard model parameters. Thus, if uncertainty is a major actor in the analysis to be made, then simplified or generalized versions of the abovementioned models may be used to allow for the increased computational requirements of a probabilistic assessment. In any case, a simplified-probabilistic approach will require less resources than a fully probabilistic approach, representing a middle ground between the fully probabilistic and deterministic approaches, thus having a good balance of level of detail in the hydrodynamic models and the ability to quantify uncertainties and exceedance rates or probabilities. In general for any type of coastal flooding, for the fully probabilistic analysis, stochastic flooding events are generated. For the simplified probabilistic analysis, a water level is identified for each return period.

For the specific case of storm surge, the fully probabilistic method applied by CIMNE et al. (2015) for the Global Assessment Report 2015 (GAR 15) can be used. This method starts by using a set of historical hurricanes for which each individual event is perturbed to generate a family of associated "children" events. Storm surge flooding (in terms of surge runup) is then computed for each newly generated event and the results are used to calculate the probability distribution of the hazard intensity (which is modeled with a Gamma distribution).

For the specific case of tsunami, a fully probabilistic hazard modeling approach, called the Probabilistic Tsunami Hazard Assessment (PTHA), was developed during the 80s (Lin and Tung, 1982; Rikitake and Aida, 1988) but was rarely used until the early 2000s when the developments of Geist and Parsons (2006) strengthened the approach that has now become more mainstream (Annaka et al., 2007; Burbidge et al., 2008; Gonzalez et al., 2009; Horspool et al., 2014; Lorito et al., 2014; Løvholt et al., 2012; Parsons and Geist, 2009; Sørensen et al., 2012; Thio et al., 2010). This PTHA, which largely relies on a Probabilistic Seismic Hazard Assessment (PSHA, (see seismic hazard section below), was used by the Norwegian Geotechnical Institute, NGI, for the Global Assessment Report 2015 (Løvholt et al., 2014a; Løvholt et al., 2014b; NGI and GA, 2015) which integrated it into a fully probabilistic risk assessment for the first time.

In general, the PTHA computes "unit" tsunami waveforms along the coast generated by each seismic source and for a unit slip. These are used to synthesize any waveform by adding (applying a principle of linear superposition) the unit waveforms each with a weight given by the slip. The seismic sources are probabilistically characterized through a recurrence model (see seismic hazard sections below for more details). In summary, the PTHA requires the following four steps (Figure 6.8). (Horspool et al., 2014; NGI and GA, 2015).

Figure 6.8. Probabilistic Tsunami Hazard Assessment



1. The PSHA is used where seismic sources are defined and subdivided into unit sub-sources and a recurrence model is applied (e.g., Gutenberg–Richter or Characteristic). See the seismic hazard section below. Here, the unit sub-sources are used to generate the unit tsunami events.

2. A unit slip is used to calculate the seafloor deformation, which becomes the initial condition of disturbance of the sea surface. Then, the tsunami waveform is propagated using linear wave theory.

3. Stochastic events are generated. For this, the maximum water level on the shore is calculated for each seismic event by applying the linear superposition principle of combining the waves from all the unit sub-sources and then scaling by the slip value for each event.

4. The maximum water levels from all seismic events are combined using the associated probability distribution functions to determine the probabilities of exceedance of the tsunami intensity (water elevation or run-up height).

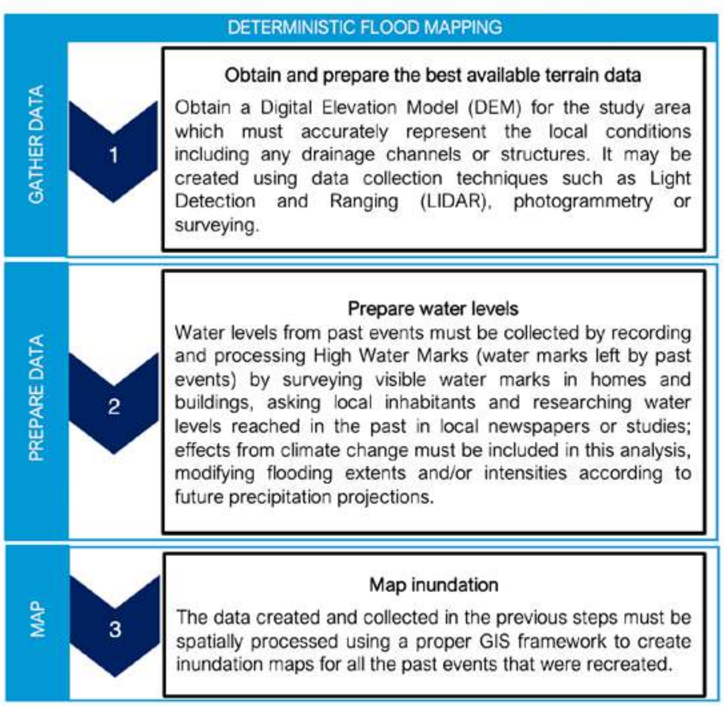
Inputs needed include bathymetry, water level time series, tidal harmonics constituents, river discharges, wind, and current, and earthquake parameters and model (tsunami only).

Deterministic Hazard Assessment: For past event or worst-case modeled events, the same coastal models discussed above are used to model individual scenarios without consideration of frequency of recurrence. Taking advantage of the fact that there are no requirements to calculate uncertainties and probabilities of occurrence that would take up additional data, computational and time resources, these models can be built to be the most detailed. For the case of tsunami, these types of assessments were widely used until around 2004 based on the fact that tsunamis, having long return periods, typically dominate the risk (Nadim and Glade, 2006) and thus a worst-case scenario was preferable (see Hebert et al., 2005; Legg et al., 2004; Lorito et al., 2008; Løvholt et al., 2006; Okal et al., 2006; Tinti and Armigliato, 2003; Venturato et al., 2007).

For past-event mapping analysis, satellite imagery may be used to demarcate the extent of the flooding. This flood polygon may be used with a digital elevation model (DEM) to determine the depth of flooding. NASA provides 30-meter DEMs for the entire world, which is a sufficient resolution for planning purposes. Another option involves using high-water marks which may be captured directly after the event to help delineate the extent of flooding. Again, this polygon area could be used with a DEM to determine depths. High-water marks can usually be found on trees, bridges, and structures directly after an event.

The National Oceanic and Atmospheric Administration (NOAA) of the United States has structured a simple Inundation Mapping method and guidance which is used as the basis for a course on Coastal Inundation Mapping offered by NOAA (NOAA, n.d.). For details on this method see NOAA's Mapping Coastal Inundation Primer (NOAA, 2012). This method, shown in Figure 6.9, consists of three steps:

Figure 6.9. Flood Mapping Process



For a modeled past event, if the water level or flow was captured by a river gauge, then the hydrologic and hydraulics models described above (for PHA) can be used with specific water level values and flows to derive a floodplain for the single event. For a modeled worst-case event, these models can be run with assumptions for the hydrologic parameters, surface roughness, and using a coarser DEM and bathymetry. A coastal flood modeling specialist should be consulted to determine the appropriate assumptions based on the region. Inputs needed include satellite imagery of the flood/surge, digital elevation model, tidal gauge value and bathymetry and high-water marks collected as points (for past event mapping); and assumed water level, assumed tidal harmonics constituents, assumed river discharges, assumed wind, and assumed current (for the modeled event).

Susceptibility Hazard Assessment: This approach involves developing a simple susceptibility map using a DEM. Areas with a lower elevation would be more likely to be flooded and would be designated in the map. The susceptibility map could also include coastline type with wetlands and highly erodible areas being designated higher than rock or hardened shorelines. These designated areas would not be associated with a return period interval. Inputs needed are DEM and coastline.

***Historical Timeline Analysis:** The last option, which applies only to the agriculture sector, is the simple method used in the Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners developed by The World Bank (2016). Within this risk approach, the hazard component is treated implicitly through the construction of a timeline of past events. This timeline of past natural hazard events is constructed for the longest time period possible (and it should be the same window of time as the agricultural production timeline to be built) and includes only coastal flooding events to determine average annual losses due to this hazard. However, a multi-hazard risk assessment may be done as well, in which case all types of hydrometeorological hazards (droughts, extreme temperatures, hurricanes) can be included in the timeline. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section for details on the risk calculation.

Box 6.2. Tips to Select Hazard Assessment Method

To perform an analysis on a group or portfolio of assets in a large area where it may be difficult to analyze each one in detail and the capture of intricacies or specific and very localized effects (such as erosion) is not required, a fully probabilistic approach may be more appropriate. In any case, if a probabilistic analysis was already conducted for the project area, it should be used.

When designing or rehabilitating individual infrastructure on the coastline where the project site[22] has no dune or other protection from water and a high level of detail is needed, a simplifiedprobabilistic or deterministic approach may be more appropriate. It will be important to know which project components could be flooded, by how much floodwater, and how much wave velocity will act on the structure. These approaches will provide more detailed hazard analysis. If hazard recurrence plays an important role, a simplifiedprobabilistic approach should be used. Otherwise, if uncertainty or hazard recurrence is not a major determinant of the hazard, a deterministic approach should be used.

Moreover, some of the coastal models require a great deal of data which may not be available for the region. If the data needed to run a fully or simplified probabilistic analysis is not available, coastal expertise in the area should be found, and a deterministic approach of recreating or modeling past events or worst-case scenarios should be followed. The information provided by a deterministic assessment can also be used to get buy-in from local stakeholders. They should be shown a deterministic past event or worst-case scenario to help influence where the project should be sited. A deterministic assessment is easier for non-technical stakeholders to understand. The deterministic assessment can be used in conjunction with a probabilistic analysis to help people understand both perspectives. A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

If the siting of the project hasn't been determined, consider moving it to higher ground away from the coastline to avoid this hazard. Next to placement of the project, another option to consider is to design the facilities allowing for a level of "allowable failure" but supporting "easy recovery." For buildings, for example, an allowable failure would be to design the lowest floor of a building so as to let flood waters easily in and out of the building without providing much of a barrier that could collapse. That design allows rapid recovery after the flooding is over. Electronic and other equipment could be installed on higher floors. See Appendix G for mode details on mitigation options.

Integration of Climate Change into the Modeling for Coastal Flood and Surge

Another consideration is the time horizon. The time horizon is how far in the future the planning will cover. The project's lifespan should be reviewed (from Step 2) to help determine the time horizon to be covered in the planning.

The primary focus of assessment for these hazards is the estimation of flood/surge extent and depths. For this reason, sea level rise is always a key climate concern. The occurrence of mean sea level rise is a given, but the exact local details are influenced by complex interactions with wind and air pressure. Like climate models, there are many different sea level rise models that produce different local results. Some approaches even consider regional fluctuations at decadal scales, as sea level is influenced by large-scale climate and ocean circulation. For shallow coastal plains where large amounts of rain might lead to inland floods, enhanced rainfall during hurricanes might also be of concern. Where mechanistic models are used in the assessment, input on other weather variables under future climate conditions may also be needed.

If there are no previous studies available for the area, the approach depends on the general question about the required level of precision. In most cases, a reasonable estimate is likely to be sufficient. In that case, a good, though conservative (low end of the possible forcing range), starting point is provided by the IPCC 5th Assessment Report chapter on sea level rise (http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter13_FINAL.pdf). An alternative starting point could be a scaling approach (Kopp et al., 2014; Perrette et al., 2013). Sea level projections have been updated since the IPCC AR5, with generally higher change projections based on more rapid ice loss at the polar ice caps than previously measured.

If needed, information on other climate components, such as wind, atmospheric pressure, rainfall, and temperature. can be obtained from one of the model archives described in Appendix E. For example, downscaled precipitation and temperature projections throughout the world are available from the Global Climate Change Viewer (http://regclim.coas.oregonstate.edu/gccv/index.html), while links to a much broader suite of model outputs, including predictions of extremes, are available from the KNMI Climate Explorer (http://climexp.knmi.nl/), among others.

Probabilistic Hazard Assessment: Climate change affects the driving forces of the coastal models. Overall precipitation and temperature are not included in wave models, so their impact on wave propagation may be neglected. However, sea level rise has a major impact on wave propagation and run-up. Sea level rise is added to the setup of most models as an additional mean water level. The changes in global wind patterns will affect the wave climate and surge; thus, for wave simulation, the time series of wave parameters or spectra should be updated to these new conditions. For models intending to predict surge and flood, the wind changes must be incorporated into the input data, as well as the atmospheric pressure, if possible.

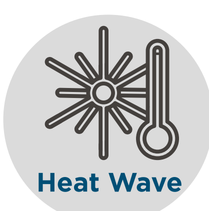
Both the wind and waves used as driving forces can come from extreme analyses and high return periods. The hydrodynamics and flood models are more sensitive to climate change. The sea level rise can be added to the setup as an additional mean water level, as was suggested for the wave models. Precipitation is not included as an input in some models, but for those where the input is required, a time series of future precipitation is required. The water volume from rainfall can be added as discharge from the rivers. Most models can include temperature as a variable, so it can be changed as an initial condition or throughout the simulation as a boundary time series. Some models can use atmospheric pressure as an input (time series). Other environmental variables, such as wind, may be added to the model for either mean or extreme conditions. Future erosion estimates based on the time horizon may be used to change the elevation model before the coastal models are implemented.

The data needed include estimates of mean sea level for time horizon of concern at the point of interest, projections of changes in future extremes of wind and atmospheric pressure to drive wave models, and projections of future extremes of rainfall and temperature (if required for the hazard assessment models).

Deterministic Hazard Assessment: For a modeled past-event or worst-case scenario, the same approach should be applied as for PHA. For a past-event mapping analysis, sea level rise should be added to the elevation identified on the satellite imagery, tidal gauge value, or high-water mark elevation. Data needed include quantitative estimates of mean sea level for time horizon of concern at the point of interest.

Susceptibility Hazard Assessment: A separate map showing sea level rise only for the time horizons appropriate for the project should be included. Then, that sea level rise elevation should be added to the susceptibility map, and additional susceptibility associated with sea level rise should be shown. Data needed include quantitative or qualitative estimates of mean sea level for the time horizon of concern at the point of interest.

6.1.4.2.4 Drought and heat wave



A drought is a deficiency of precipitation over an extended period of time—usually one or more seasons—resulting in a water shortage for some activity, group, or environmental sector (National Drought Mitigation Center, 2018). It is difficult to define because regions experience impacts at different levels of dryness. An arid region is used to little precipitation, while wet regions are accustomed to ample precipitation amounts. Droughts can therefore be also defined based on application. Meteorological droughts focus on different aspects of water deficits than agricultural or hydrologic droughts. Meteorological drought focuses on the occurrence of dry weather patterns in an area. Agricultural drought occurs when there is not enough water content in the soils to satisfy the water demand from crops and includes the consideration of soil and crop evapotranspiration. Hydrological drought focuses on the occurrence of an evident low water supply in streams, reservoirs, and groundwater levels.

A heat wave can be characterized by a deviation in temperature above the local average or as a deviation beyond the 95^{th} percentile of the observed daily temperatures for three or more days. Some heat waves are defined by the combination of temperature and humidity to indicate that control of body temperature might become difficult (e.g., when the heat index rises above human skin temperature). Definitions vary depending on the location and the problem.

The following are the three dimensions of a hazard analysis for drought and heatwave hazards.

- *Extent:* These hazards have more of a regional influence, so their extent is typically larger than for more localized hazards such as landslides or flooding.

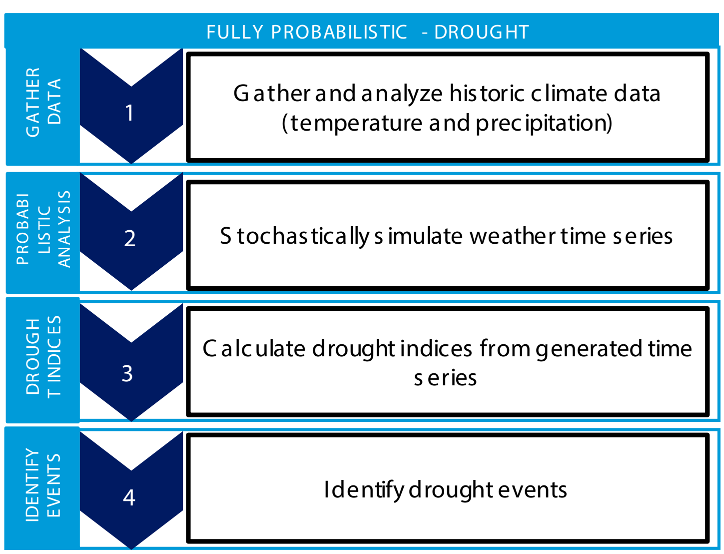
- *Intensity:* The intensity of a heat wave is a deviation in degrees of temperature from the normal state. In the inner tropics, a deviation of 2 degrees from the normal would make a heat wave. The intensity of a drought can be measured by precipitation amounts. For drought hazard, indices are also typically used to represent the intensity. The Palmer Drought Severity Index (PDSI) measures both the wetness (positive value) and dryness (negative values) in the environment, based on the supply and demand concept of the water balance equation. This index incorporates cumulative precipitation in past months, moisture supply, runoff, and evaporation demand at the surface level. The Standardized Precipitation Index (SPI) is based exclusively on precipitation and its cumulative anomalies, which in a region translate into water resources: soil moisture, groundwater, snowpack, river discharges, and reservoir storages. The time scale over which water deficits accumulate is extremely important for this index, but it is not recommended for climate change impacts because it does not take evapotranspiration into consideration. The index that includes evapotranspiration is the Standardized Precipitation-Evapotranspiration Index (SPEI), which augments the precipitation-based SPI to better capture loss of moisture from the ground. As with all drought indices that use evapotranspiration, they are very sensitive to the selection of the function used, which will determine their sensitivity to temperature changes. It is still not clear which formulation is the best to be used globally or in specific regions.

- *Frequency:* Likelihood is often estimated statistically from previous events in the region. Since these three hazards are usually regional, data for the region would be required.

Details on the application of the three hazard assessment methods (probabilistic, deterministic and susceptibility) are described next. Specific models are detailed in Appendix D.

Probabilistic Hazard Assessment: A PHA approach is not commonly used to represent heatwaves; deterministic and susceptibility analyses are used instead. Historically, the use of a probabilistic hazard assessment framework for drought has been rare, mainly because of the complexity of droughts that differentiates them from other better-known hazards. However, in recent years researchers have started to develop and tailor probabilistic approaches that can work with drought. The approach proposed by Bernal et al. (2017) to apply a fully probabilistic risk framework for this hazard represents one of the most complete and thorough approaches, as it maintains the technical complexity of modeling droughts (agricultural droughts) and embeds it in a robust probabilistic risk setting that allows all the usual probabilistic risk metrics to be obtained. Figure 6.10 summarizes the proposed PHA for drought.

Figure 6.10. Main Steps in a Probabilistic Drought Hazard Assessment



1. Historic time series of precipitation (daily) and temperature (minimum, mean, and maximum) from local gauges (or from remote sensing data for cases with a lack of local data) are gathered.

2. A probability analysis is applied to the time series, where probability distributions are assigned to each variable in each local station and for each day of the year. These distributions are then used to simulate new time series that include events that have not necessarily occurred yet. Temporal autocorrelation and spatial correlation procedures are applied to avoid abrupt changes both in time and space for the variables.

3. Indices are used to identify out-of-the-norm conditions and define the duration and severity of a drought event. Various drought indices are selected and tested to determine the best-fitting index for the study area (a statistical fitting is made of the computed index parameters to the index's theoretical probability distribution). If the selected indices include evapotranspiration, this additional variable should be calculated. Additionally, a time scale (defining the length of time over which the weather variables are accumulated prior to the time of the calculation of the index) is set. The selected index is calculated for the stochastic time series.

4. In the creation of hazard scenarios, drought events were defined as events of simultaneous and continuous deficit in precipitation and elevated temperatures represented by a value below a defined threshold of the selected drought index. Each drought event has a duration and severity. The severity of a drought event is then defined as the cumulative index value during the event (area under the index curve of the event). An additional measure can be computed by dividing the severity by the duration to obtain a unit measure of the severity: this is referred to as intensity. Drought events are identified in the time series for each station. Then, drought events that occur simultaneously in various stations are identified to find regional drought events. These final regional drought events (which have an associated frequency of occurrence computed from the total time that was simulated) are drought scenarios comprising the drought hazard module.

A probabilistic hazard assessment approach is not commonly used to represent heatwaves, thus deterministic and susceptibility analyses are used instead.

Inputs needed include time series of climate and land variables, including temperature, precipitation, moisture supply, runoff, and evaporation.

Deterministic Hazard Assessment: Sometimes the highly detailed model inputs of soil characteristics, cloudiness, windspeeds, and others are not available and other approaches must be taken to help identify the hazard. SPI and SPEI offer relatively simple estimates based on readily available climate data. The models described above for a PHA should be used to conduct a modeled worst-case event, if the data are available, or the indices should be used to model an event. In many cases, the event may take up the entire region; this may be helpful if the project spans a large geographic area. CLIMDEX (Environment Canada http://www.cccma.ec.gc.ca/data/climdex/climdex.shtml) provides a list of indices that capture various aspects of temperature and precipitation characteristics, including information on consecutive dry days. Changes in overall water availability can be analyzed at several levels, from simple to complex.

To conduct a past event mapping analysis, it is important to check whether previous events have been mapped. In some cases, tree-ring records offer insight into past occurrence, duration, and intensities of droughts.

Inputs needed include time series or indices of climate and land variables (for modeled event), or hazard characteristics of each historical event including land cover, location, and intensity (for past event mapping analysis).

Susceptibility Hazard Assessment: This approach involves developing a simple susceptibility map (drought index map) using different data, including temperature, precipitation, moisture supply, runoff, and evaporation water sources, dark surfaces (for heatwave), and previous events. These designated areas would not be associated with a return period interval.

Inputs needed include previous hazard events, dark surfaces, and water resources.

***Historical Timeline Analysis:** The last option, which applies only to the agriculture sector, is the simple method used in the Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners developed by the World Bank (2016). Within this risk approach, the hazard component is treated implicitly through the construction of a timeline of past events. This timeline of past natural hazard events shall be constructed for the longest time period possible (and it should be the same window of time as the agricultural production timeline to be built) and shall include only drought or heatwave events to determine average annual losses due to these individual hazards. However, a multi-hazard risk assessment may be done as well, in which case all types of hydrometeorological hazards (floods, extreme temperatures, hurricanes) can be included in the timeline. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section below for details on the risk calculation.

Box 6.3. Tips to Select Hazard Assessment Method

To perform an analysis on a group or portfolio of assets in a large area where it may be difficult to analyze each one in detail and the capture of intricacies or specific and very localized effects is not required, then a fully probabilistic approach may be more appropriate. In any case, if a probabilistic analysis was already conducted for the project area, it should be used.

If the study area is prone to these hazards, the project type is highly vulnerable to these hazards (such as an agricultural project) and a high level of detail is needed, a simplified probabilistic or deterministic approach may be more appropriate. It is necessary to know which project components are susceptible to these hazards. These approaches will provide more detailed hazard analysis. If hazard recurrence plays an important role, use a simplified probabilistic approach. Otherwise, if uncertainty or hazard recurrence is not a major determinant of the hazard, use a deterministic approach.

Moreover, some of the drought models require a great deal of data which may not be available for the region. If the data needed to run a fully or simplified probabilistic analysis are not available, a deterministic approach of recreating or modeling past events or worst-case scenarios should be used. The information provided by a deterministic assessment can also be used to get buy-in from local stakeholders, so they could be shown a deterministic past event or worst-case scenario to help influence where the project should be sited. A deterministic assessment is easier for non-technical stakeholders to understand. The deterministic assessment can be used in conjunction with a probabilistic analysis to help people understand both perspectives.

A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

Integration of Climate Change into the Modeling for Drought and Heat Wave

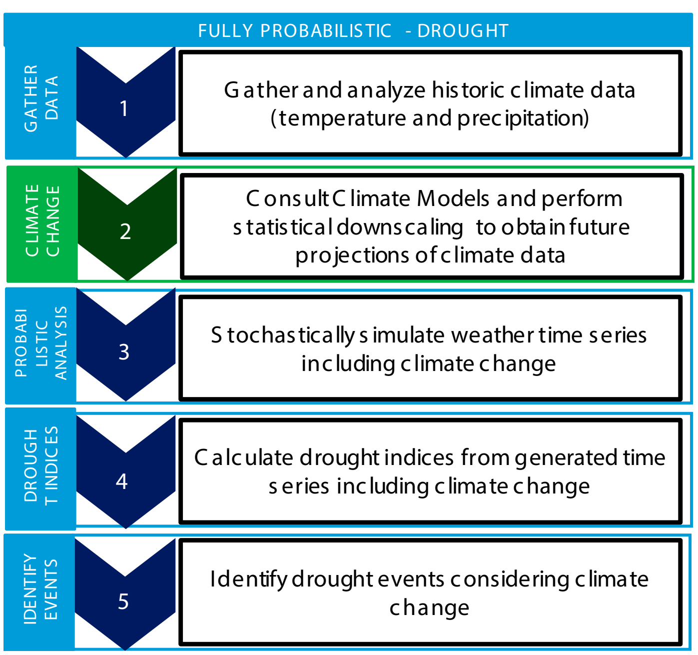
It is good to establish a critical set of criteria for each hazard. Many will depend on the application or the societal or ecological vulnerabilities in a region. What temperatures and duration are considered a heat wave? How much of a deficit of precipitation over what period constitutes a drought? These thresholds are important when integrating climate change into the models. Once these criteria are set, climate models can be used to predict how often the hazard will occur in the future.

Heatwave hazard is directly related to changes in extreme air temperature and humidity (summarized by the heat index). Drought and water scarcity hazards are tied to the overall water balance of the area and so are less directly tied to GCM predictions.

Specific considerations for the three hazard assessment methods are given next.

Probabilistic Hazard Assessment: The probabilistic drought hazard assessment proposed by Bernal et al. (2017) presented above allows a seamless incorporation of climate change effects by conducting a statistical downscaling analysis to obtain future projections for the study area and then applying the changes directly in the weather generator to obtain stochastically simulated time series that incorporate the effect of climate change. Figure 6.11 summarizes the process.

Figure 6.11. Main Steps in a Probabilistic Drought Hazard Assessment



Modeled past-event or worst-case analysis of a Deterministic Hazard Assessment: The future probability of this hazard should be determined by looking at the trends in precipitation (particularly monthly or seasonal), relative humidity, the probability of number of dry days, and the average and maximum temperatures. For heatwaves, the duration for different heat thresholds and the seasonality of occurrence should be assessed. For drought, the expected change in occurrence of consecutive dry days and/or changes in the overall water balance should be identified. Particular attention should be paid to variability: the mean of a certain threshold (e.g., 30 successive dry days) might be a composite of years with only short dry sequences with years with much longer dry intervals. Although CLIMDEX is not a projections database per se, different archives, such as the World Bank's Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/), offer CLIMDEX indicators applied to CMIP5 or other data.[23] Future likelihoods and magnitudes should be modeled. Weather generators may also be integrated into the approach to provide a longer time series.

Data needed: For drought, generally monthly data are sufficient, though some "flash droughts" connected with heat waves can impose hazards on shorter time windows. Heat waves require daily data, and very often daily minimum and maximum temperatures are required. Relative humidity is also useful for heat index calculations.

Susceptibility Hazard Assessment or past-event mapping analysis of a Deterministic Hazard Assessment: The climate models should be reviewed to determine if these hazards are expected to increase in likelihood and/or frequency over time. If so, this should be noted in the maps. In many cases, summary information from regional information summaries such as those provided in the IPCC reports or the World Bank Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/) may be sufficient to evaluate climate considerations for

23 When accessing the Portal, a country or region should be selected, Climate Data chosen, then Projections, then using the dropdown menu under Variables the list of indicators should be opened and the desired indicators selected.

this hazard. Output from water balance models applied to GCMs is also available from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) at https://www.isimip.org/.

6.1.4.2.5 Earthquake

The three dimensions of a hazard analysis are discussed next for seismic hazard.

- *Extent:* Earthquakes have large areas of influence given the scale of plate tectonics and faults; thus, it is important to highlight that even though the area of interest for analysis may be small, faults and plate boundaries located outside this area (at regional level at least) should be taken into account when modeling seismic hazard.

- *Intensity:* It is important to distinguish between the main focus of this document, intensity, and the magnitude of an earthquake. The magnitude of an earthquake measures the amount of energy released and is used as a measure of its size (the Richter scale, also known as the Local Magnitude - M_L - scale, is the original measure of magnitude; however, currently the Moment Magnitude - M_W - measure is preferred). Intensity measures the level of shaking at ground level that an earthquake of certain magnitude can generate. Intensity is thus the value of ground acceleration, velocity or displacement felt at a site.[24] Furthermore, the intensity (and not the magnitude) of an earthquake is directly linked to the level of damage that it can cause. The most common variable used to represent the intensity of an earthquake is ground acceleration in cm/s^2 (also called *gal*) or as a fraction of gravity (e.g. 0.2 g); specifically, peak ground acceleration (PGA) and spectral acceleration (acceleration felt by different vibration or structural periods, e.g. 0.3 s or 1.0 s) values. Peak ground velocity (PGV) and peak ground displacement (PGD) are also used.

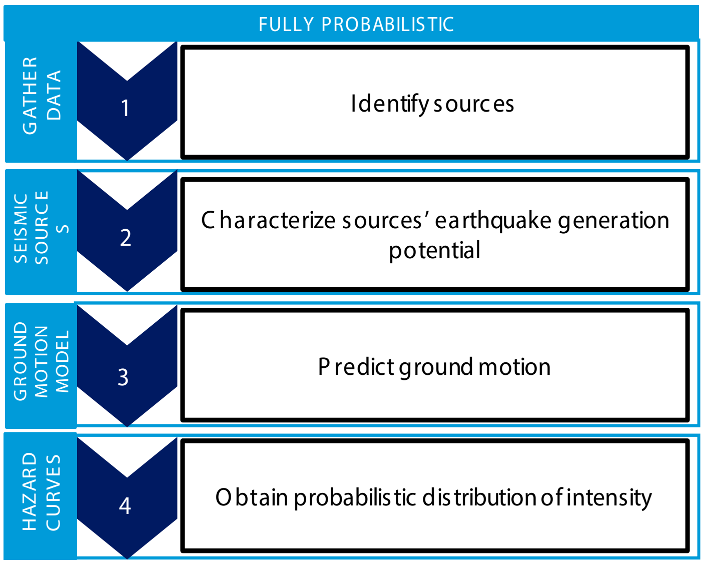
- *Frequency:* The frequency of occurrence of earthquakes of different magnitudes for seismic sources and the frequency of occurrence of intensity levels at specified locations are key characteristics. A plot of earthquake magnitude versus annual rate of occurrence, or magnitude recurrence plot, shows the propensity of a source to generate small and large earthquakes and is used to characterize individual sources. On the other hand, a plot of intensity (e.g., PGA) versus annual rate of exceedance is called a hazard curve and is used in probabilistic assessments to represent the resulting intensity levels considering all possible earthquakes.

Details on the application of the three hazard assessment methods (probabilistic, deterministic, and susceptibility) are described next.

Probabilistic Hazard Assessment: In the field of earthquake engineering, the fully probabilistic method is a standard (known as Probabilistic Seismic Hazard Assessment, or PSHA). Originally proposed by Cornell (1968), it has been widely used for many years all over the world to construct the official models used by countries and international institutions (including the International Code Council (ICC) and its International Building Code (IBC). go to https://www.iccsafe.org/codes-tech-support/codes/2018-i-codes/ibc/) to be included in building codes. Unlike scenario-specific approaches, the PSHA considers the contribution of all seismic sources and all the corresponding potential events that may influence a determined area of interest. In general, the PSHA requires the following four steps (Figure 6.12). Baker (2008) discusses this further.

24 An earthquake with a certain magnitude generates different intensities that are felt in different places, e.g., the acceleration (intensity) felt at a location 30 km away from the hypocenter of an earthquake with M_w 6 is much higher than the acceleration (intensity) felt due to the same earthquake at another location 100 km away from the hypocenter.

Figure 6.12. Probabilistic Seismic Hazard Assessment



1. Identify sources: All seismic sources with the capacity of generating damaging earthquakes must be identified. A source is a modelled entity that can generate earthquakes, and as such may represent individual or grouped faults (as lines or planes), point sources, or larger areas (as planes) such as subduction areas or background areas (areas with sparse activity not easily attributed to a specific geometry or location). Geologic data and studies of active faults and plate tectonics are usually consulted to help in this identification.

2. The potential of each source to generate earthquakes must be characterized. Magnitude recurrence plots are used to characterize sources in terms of the (annual) rates of occurrence of earthquakes with varying magnitudes. A catalogue of all past earthquakes is used to assign sub-sets of events to individual sources and statistical analyses (usually) Poisson's seismicity model and the Gutenberg-Richter relationship are used) (Cornell, 1968) are then applied to obtain plots for each source.

3. The probability distribution of shaking intensity as a function of magnitude and distance is modelled. Ground motion prediction equations, or GMPE (also called attenuation relations) describe the way in which seismic waves are attenuated as they travel through the Earth's crust, and as such they provide estimates of the resulting intensity (acceleration, velocity, or displacement that the ground experiences) felt from an earthquake with a certain magnitude, at different distances from the hypocenter of the earthquake. Furthermore, they describe the probability density function of the ground motion given the properties of the earthquake source (magnitude, style-of-faulting), the wave propagation (distance), and site response. In nearly all cases, the ground motion is assumed to follow a lognormal distribution, and the ground motion equation gives the median ground motion and the standard deviation in log units. Scientific literature provides an extensive menu of GMPE that can be used, and usually researchers have already developed these relationships for specific countries or tectonic settings.

4. Apply probability theory (Total Probability Theorem and the assumption that the intensity follows a lognormal distribution) to mathematically combine earthquake magnitude recurrence, location and attenuation characteristics for all sources to obtain a distribution of intensities in the area of interest (hazard curves).

It is key that PSHA include site effects from soils since the soil type is linked to amplification factors for peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration (in general the looser the soil material, the more amplification of PGA, PGV, and spectral acceleration). This may be done in two ways. The first involves including soil classes directly within the third step of the PSHA by selecting pre-established soil classes (usually the NEHRP site classification is used; see BSSC, 2004) for the area of interest and using GMPE that include those classes. The second one involves using local microzonation studies where the upper 30 meters of geology are assessed and the shear wave velocity profile of the soils is determined, from where amplification factors can be derived and applied to the results of a rock level PSHA.

A simplified probabilistic analysis involves using existing integrated hazard maps and directly reading the corresponding intensity or intensities for the location of interest for a few selected return periods. These maps could be the hazard maps for the Design Ground Motion (usually corresponding to the hazard map with a return period of 475 years) or maps with 1,000 or 2,500-year return periods.

Deterministic Hazard Assessment: In deterministic analyses, a single event or scenario is modelled or recreated and analyzed. This involves selecting a single or a couple of separate events that may be past earthquakes, a design earthquake, or a maximum (worst-case) earthquake.

To conduct a past-event analysis, it is important find out whether ground-shaking data for previous events exists near the project site. Sometimes universities and other organizations develop ground-shaking maps after an event (the U. S. Geological Survey has an earthquake catalog and portal where events from around the world are reported and analyzed, always producing shakemaps. See https://earthquake.usgs.gov/earthquakes/search/ or https://prod-earthquake.cr.usgs.gov/ earthquakes/map/).

A worst-case event analysis involves modeling the physics of an earthquake by establishing the characteristics of a worst-case scenario in terms of magnitude (e.g., M_W 7), location (specific seismic source, longitude and latitude), mechanism and depth (depth of the hypocenter), and applying a physically based model.

Susceptibility Hazard Assessment: The last approach is to develop a simple susceptibility map using soils data, fault lines, and historical earthquake data. These designated areas would not be associated with a return period interval. This approach is especially useful for liquefaction assessments, as these are not commonly modeled probabilistically. Liquefaction susceptibility can be identified using geologic maps of the area typically identifying the age, depositional environment, and material type for a particular mapped geologic unit. Based on these characteristics, a relative liquefaction susceptibility rating can be assigned. Mapped areas of geological material characterized as rock or rock-like are considered to present no liquefaction hazard. Relationships between liquefaction and peak horizontal ground acceleration can then be used to determine the local ground-shaking value.

Specific software to run models are detailed in Appendix D. Box 6.4 presents guidance to help determine which approach is more appropriate depending on the circumstances.

Box 6.4. Tips to Select Hazard Assessment Method

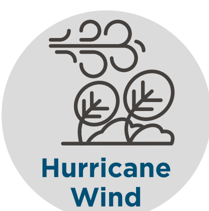
To perform an analysis on a group or portfolio of assets in a large area where it may be difficult to analyze each one in detail and the capture of intricacies or specific and very localized effects is not required, a fully probabilistic approach may be more appropriate. In any case, if a probabilistic analysis was already conducted for the project area, it should be used. If the data needed to run a fully probabilistic analysis are not available, it should be determined if there are local building regulations associated with seismic design (an engineer may need to provide design guidance) and design maps should be used for a simplified probabilistic approach. It will be important to know which areas and which project components are exposed to loose soil and liquefaction.

If individual infrastructure is being designed or rehabilitated in a high seismic hazard zone and a high level of detail is needed, a simplified probabilistic or deterministic approach may be more appropriate. It will be necessary to know exactly which project components are exposed to loose soils and liquefaction. These approaches will provide more detailed hazard analysis. If hazard recurrence plays an important role, a simplified probabilistic approach should be used. Otherwise, if uncertainty or hazard recurrence is not a major determinant of the hazard, a deterministic approach should be used.

The information provided by a deterministic assessment can also be used to get buy-in from local stakeholders. Thus, they should be shown a deterministic past event or worst-case scenario to help influence the siting of the project. A deterministic assessment is easier for non-technical stakeholders to understand. The deterministic can be used in conjunction with a probabilistic analysis to help people understand both perspectives.

A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

6.1.4.2.6 Hurricane Wind



The three dimensions of a hazard analysis are discussed next for hurricane wind.

- *Extent:* Tropical storms and hurricanes have large areas of influence given the scale of the phenomenon; thus, even though the area of interest for analysis may be small and not necessarily located on the coast, the location of the area within the Caribbean and Pacific basins (at regional level) should be taken into account.
- *Intensity:* Wind speed.
- *Frequency:* As with hurricane storm surge, hurricane winds also have an associated return period (an average of how often it can occur), with small intensities occurring very frequently and large intensities occurring very rarely. Usually, engineers use wind speed values in gusts with specific return periods to design infrastructure. Additionally, a plot of intensity (e.g., wind speed) versus annual rate of exceedance is called a hazard curve and is used in fully probabilistic assessments to represent the resulting intensity levels considering all possible events.

Details on the application of the three hazard assessment methods (probabilistic, deterministic, and susceptibility) are described next. Specific models are detailed in Appendix D.

Probabilistic Hazard Assessment: For a fully probabilistic approach and as in the case of storm surge, in addition to the wind model, a tropical storm or hurricane model must be used as the generating core of hurricane events. For this, the method applied by CIMNE et al. (2015) for the Global Assessment Report 2015 (GAR 15) can be used. This method starts by using a set of historical hurricanes for which each individual event is perturbed using a Wiener process to generate a family of associated "children" events. Wind speed (in terms of peak wind speed of 3-second gusts) is then computed for each newly generated event, and the results are used to calculate the probability distribution of the hazard intensity (which is modeled with a Gamma distribution). Please see CIMNE et al. (2015) for details.

In summary, the following are key components of building a hurricane wind model of a fully probabilistic assessment:

- *Hurricane Track Simulation Model.* Mathematical simulation of hurricanes, such as the one described above by CIMEN et al. (2015), is the most accepted approach for estimating wind speeds for the design of structures and assessment of hurricane risk. The basic approach in all previously published hurricane simulation studies is the same in that site-specific statistics of key hurricane parameters (including central pressure difference (Dp), Holland pressure profile parameter (B), radius to maximum winds (Rmax), heading (Q), translation speed (c), and the coast crossing position or distance of closest approach (dmin)) are first obtained. Since the statistical distributions of these key hurricane parameters are known from historical data, a Monte Carlo approach can be used to sample values from each of the aforementioned distributions. A mathematical representation of a hurricane is passed along the straight-line path, satisfying the sampled data, while the simulated wind speeds are recorded. The intensity of the hurricane is held constant until landfall is achieved, after which time the hurricane is decayed using filling rate models. The storm track simulation model is initiated by randomly sampling a starting position, date, time, heading, and translation speed from one of the tropical storms from historical records.

- *Hurricane Wind Field Model:* A critical component of simulating hurricanes is a good representation of the hurricane wind field given information regarding the storm intensity, size, and translation speed. The hurricane wind field model has two components. The first component is the overall mean flow field describing the upper level winds, and the second is the boundary layer model used to estimate wind speeds at the surface of the earth, given the upper level wind speeds.

  The mean flow field model solves the full nonlinear equations of motion of a translating hurricane and then parameterizes these for use in fast running simulations. The use of a full numerical solution to the equations of motion for a hurricane enables the modeling of asymmetries in the storm that arise from the complex interaction of the frictional forces and the winds, which vary throughout the storm. They can produce very high wind speeds, wrapping around the eyewall in some small and intense storms. The use of simple empirical models to define the hurricane will not reproduce these effects.

  The hurricane boundary layer model is developed using a combination of velocity profiles computed using dropsonde data and a linear theoretical hurricane boundary layer model. The hurricane boundary layer model incorporates a combined logarithmic-quadratic variation of the mean wind speed with height used to replicate the height of the low-level jet observed in the hurricane boundary layer. This allows a more realistic representation of the wind speeds near the surface, and better estimates of the effect of the sea-land interface in reducing wind speeds near the coast.

- *Surface Roughness.* A critical component in the modeling of wind effects, damage, and loss to buildings and facilities is the assessment and modelling of ground roughness. As the ground surface becomes rougher, the wind speeds near the ground decrease, although the upper level wind speed remains the same. The wind loads experienced by structures located in a typical peri-urban, treed, or urban environment are much lower than those experienced by buildings located in relatively unobstructed regions such as waterfront and open field locations. The wind loads experienced by one- and two-story structures located in forested areas may be as low as one half of those experienced by similar structures located in an open environment.

The effect of surface roughness is treated in a simple fashion in building codes and standards using exposure categories. For example, open terrain and suburban terrain are designated as Exposures C and B, respectively, in version seven of the American Society of Civil Engineers Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE-7). The approach taken in most international standards is to define a basic wind speed, which represents the wind speed at a height of 10 m in open terrain. The effect of the actual local terrain is then considered by modifying that wind speed by a factor, which is dictated by the exposure category for the local terrain. This table is provided in Appendix D.

- *Windborne Debris Models: A* significant amount of the damage to structures associated with hurricane winds is produced by windborne debris impacting buildings and damaging building exteriors, including roof covering, windows, doors, and other openings. There can be different debris models depending on the type of environment—residential vs. commercial and industrial. Residential models include failed roofing and trees, while a commercial model may include gravel found on commercial rooftops.

For a simplified probabilistic assessment, and when physical models cannot be built due to restrictions on data or resources, statistical models can be used to evaluate observed data such as wind speeds and central pressures. These models are often used to evaluate extremes or peaks to determine the frequency distribution of wind speeds. The outputs of these models can be used to generate wind speeds associated with a particular return period interval.

Inputs needed include time series on wind speeds (along with central pressure differences (Dp), Holland pressure profile parameters (B), radius to maximum winds (Rmax), headings (Q), and translation speeds (c))—particularly peak gusts—storm intensity, size, and translation speed and landcover data.

Deterministic Hazard Assessment: To conduct a past-event mapping or modeling analysis, it is necessary to find out if wind data exists near the project site for a particular event. Sometimes universities and other organizations develop wind speed maps after an event.

Inputs needed include details on wind speeds, storm intensity, size, and translation speed for one event, landcover data, and mapped locations of maximum wind speeds for specific event.

Susceptibility Hazard Assessment: This approach involves developing a simple susceptibility map using distance from the coastline and creating buffers from historical hurricane tracts (https://oceanservice.noaa.gov/news/historical-hurricanes/). These designated areas would not be associated with a return period interval.

Inputs needed include distance from shoreline and historical hurricane tracts.

***Historical Timeline Analysis:** The last option, which applies only to the agriculture sector, is the simple method used in the Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners developed by the World Bank (2016). Within this risk approach, the hazard component is treated implicitly through the construction of a timeline of past events. This timeline of past natural hazard events shall be constructed for the longest time period possible (and it should be the same window of time as the agricultural production timeline to be built) and shall include only coastal hurricane events to determine average annual losses due to this hazard. However, a multi-hazard risk assessment may be done as well, in which case all types of hydrometeorological hazards (droughts, extreme temperatures, floods) can be included in the timeline. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section below for details on the risk calculation.

Box 6.5. Tips to Select Hazard Assessment Method

To perform an analysis on a group or portfolio of assets in a large area where it may be difficult to analyze each one in detail and the capture of intricacies or specific and very localized effects (such as erosion) is not required, a fully probabilistic approach may be more appropriate. In any case, if a probabilistic analysis was already conducted for the project area, it should be used. If the data to run a fully probabilistic assessment is not available, it should be determined whether there are local building regulations associated with wind speed mapping for a simplified probabilistic approach.

If individual infrastructure is being designed or rehabilitated on the coastline and a high level of detail is needed, a simplifiedprobabilistic or deterministic approach may be more appropriate. It will be necessary to know which project components are exposed to the high wind speeds and the magnitude of those wind speeds. These approaches will provide a more detailed hazard analysis. If hazard recurrence plays an important role, a simplifiedprobabilistic approach should be used. Otherwise, if uncertainty or hazard recurrence is not a major determinant of the hazard, a deterministic approach should be used.

Moreover, some hurricane wind models require a great deal of data which may not be available for the region. If the data needed to run a fully or simplifiedprobabilistic analysis is not available, an engineer should review historic hurricanes and identify an appropriate design wind speed for a deterministic approach. The information provided by a deterministic assessment can also be used to get buy-in from local stakeholders. They should be shown a deterministic past event or worst-case scenario to help influence the siting of the project. A deterministic assessment is easier for non-technical stakeholders to understand. The deterministic can be used in conjunction with a probabilistic analysis to help people understand both perspectives.
A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

Integration of Climate Change into the modelling for Hurricane Wind Speed

Climate change by the end of the 21st century will likely cause tropical cyclones globally to be more intense on average (by 2 to 11 percent, according to model projections for an IPCC mid-range scenario) (NOAA GFDL, 2018). This change would imply an even larger percentage increase in the destructive potential per storm, assuming no reduction in storm size. There are better than even odds that anthropogenic warming over the next century will lead to an increase in the occurrence of very intense tropical cyclones globally–an increase that would be substantially larger in percentage terms than the 2 to 11 percent increase in the average storm intensity. This increase in intense storm occurrence is projected despite a likely decrease (or little change) in the global numbers of all tropical cyclones. However, there is at present only low confidence that such an increase in very intense storms will occur in the Atlantic basin. Additionally, at this time there are no reliable tools for forecasting changes in specific geographic areas. Therefore, a conservative safety factor approach is used.

Hurricane wind occurrence is not only tied to the strength of the storm; it also contains possible changes in the spatial distribution of occurrence as well as speed of hurricane movement. There are some indications that higher sea surface temperatures have led to an expansion of the regions where hurricane development and/or occurrence can be expected. A longer survival of hurricanes into higher latitudes is expected, although the magnitude varies regionally. The movement of hurricanes is important because even lower-intensity hurricanes that remain in a region longer could have similar effects or impacts as more intense events. As of now, there is no robust indication that the speed will change systematically.

Finally, an additional element of tropical cyclone impacts on a region is rainfall. As discussed under flooding, the robust projections of increased warming across the planet would point to the potential of higher precipitation amounts. The Clausius-Clapeyron relationship provides an estimate of up to 7 percent increase in water-carrying capacity per degree Celsius warming. Therefore, substantial increases in hurricane-related rainfall are to be expected.

Specific considerations for the three hazard assessment methods are given next.

Probabilistic Hazard Assessment or Deterministic Hazard Assessment: For a probabilistic assessment simulations employing dynamical models driven by slightly perturbed locations from observed events are useful (e.g., Tropical Cyclone Risk Model by Australia Geoscience). This approach more faithfully covers the spatial extent beyond the narrow, observed tracks. A conservative approach should be considered, increasing the intensity by 11 percent and likelihood by the same amount and allowing for a potential spatial expansion of the domain with tropical cycles poleward by about 50-100km per decade. If modeling is not possible, results from such simulations can be consulted in the form of products such as 100-year return period cyclonic wind hazard (Vigh, 2018).

If considering tropical cyclone risk for an area just outside of historical occurrence of such storms, it might be useful to allow for a spatial expansion of the domain with expected events in the future, particularly toward the end of the 21st century. Estimates of poleward expansion range from 20 to almost 100 km per decade.

Data needed: homogenized tropical cyclone track and intensity information (e.g., IBTrACS: https://www.ncdc.noaa.gov/ibtracs/)

Susceptibility Hazard Assessment: A buffer should be added to the delineated areas. High wind areas should be delineated (155 km/h or greater).

6.1.4.2.7 Landslide

Couture (2011: 60) described landslide hazard as "division of land into somewhat homogeneous areas or domains, and their ranking according to the degrees of actual or potential landslide susceptibility, hazard or risk or by applicability of certain landslide-related regulations." Several approaches for landslide hazard mapping have been developed, including inventory-based mapping, heuristic approaches, probabilistic assessments, deterministic approaches, statistical analysis, and multi criteria decision making. Most of these models create hazard zones that divide the areas by ranking. Specific software is detailed in Appendix D. The three dimensions of a hazard analysis for landslides are defined as follows.

- *Extent:* Landslides are local events and as such tend to have smaller or limited spatial extents compared to those of other hazards, such as earthquakes or floods.

- *Intensity:* Debris volume.

- *Frequency:* Likelihood is often estimated statistically from previous events in the region.

The following are details on the application of the three hazard assessment methods (probabilistic, deterministic, and susceptibility).

Probabilistic Hazard Assessment: The probabilistic landslide hazard assessment helps to determine spatial, temporal and size probability of landslides (Guzzetti et al., 2005b). The fully probabilistic approach of simulating stochastic events is rare for landslide hazard because of its complexity. Instead, simplified probabilistic methods of landslide mapping that are less complex are better suited. In the simplified probabilistic approach to landslide identification, the spatial distribution of landslides is compared with various explanatory variables (with assigned weights) within a probabilistic framework (Kanungo et al., 2009). It includes Bayesian probability, certainty factor, favorability function, and others. The degree of relationship between each thematic data layer with landslide distribution is transformed to a value based on a probability distribution function. This approach is quantitative, but a certain degree of subjectivity exists in the weight assignment procedure (Kanungo et al. 2009). This may be complemented by coupling a rainfall and earthquake trigger model to properly represent this hazard.

Rainfall threshold model: Rainfall threshold for landsliding refers to the minimum intensity or duration of rainfall necessary to cause a landslide (Varnes and IAEG, 1984). Cumulative rainfall, antecedent rainfall, rainfall intensity, and rainfall duration are the most commonly used parameters to design rainfall threshold. The critical rainfall threshold model (Qcr) is based on soil properties, slope angle, upslope drainage, wet soil bulk density, and density of water. Several studies on landslide susceptibility assessment have used Qcr to predict landslides. The rainfall threshold decreases with increasing seasonal accumulation and becomes constant at 11 mm/day (Gabet et al., 2004). Cardona et al. (2017a) explain the application of a rainfall trigger model to landslides.

Earthquake trigger model: This model uses a critical acceleration trigger, defined as the minimum ground acceleration (caused by an earthquake) that would cause a landslide (Newmark, 1965). The critical acceleration is a function of the factor of safety (FS). As such, it becomes another inherent characteristic of a slope, independent of a given seismic event; it would be the seismic susceptibility to landslides (Jibson et al., 1998; 2000). Traditional geotechnical techniques, such as the Infinite Slope Analysis, may be applied to determine the FS. Critical acceleration is then used in conjunction with an earthquake model to compute the probability of exceeding the critical acceleration and ultimately, of landslides. See Cardona et al. (2017a) for details on the application of this earthquake trigger model to landslides.

Inputs needed include frequency-volume statistics, DEM, soils, landcover, slope angle, and the specific rainfall or earthquake trigger model inputs discussed above (time series precipitation, ground shaking).

Deterministic Hazard Assessment: Both the rainfall and earthquake trigger models can be applied to probabilistic and deterministic hazard assessments. For the DHA, individual events or scenarios can be chosen to represent, for example, an extreme rainfall event or earthquake. These are analyzed together with the other parameters, including slope, soil properties, and drainage properties.

Inputs needed include previous landslide locations, DEM, soil properties, landcover, time series precipitation, water saturation, slope angle, upslope drainage, wet soil bulk density, and ground shaking.

Susceptibility Hazard Assessment: Probabilistic and determinist approaches to assess landslide hazard are not very common, as they require a lot of data and complex models; consequently, susceptibility models bridge this gap and have become widespread. Three approaches to develop susceptibility assessments—physically based methods, statistical methods and inventory methods—are described below.

Physically based landslide susceptibility methods. Physically based methods for landslide hazard assessment describe physical processes leading to the landslide event and are based on simple mechanical laws. These models account for the transient groundwater response of slope to rainfall (Kuriakose 2010). These models do not need long-term landslide data and therefore can also be applicable to areas with incomplete landslide inventories (Kuriakose 2010).

Statistical methods (bi-variate and multi-variate). The bi-variate statistical analysis for landslide hazard identification compares each data layer of causative factors to the existing landslide distribution (Kanungo et al. 2009). Weights are assigned to the landslide's causative factors based on landslide density. The frequency analysis approach, the information value model , the weights of evidence model, and the weighted overlay model are bi-variate statistical methods used in landslide mapping. The multi-variate statistical analysis for landslide hazard identification considers the relative contribution of each thematic data layer to total landslide susceptibility (Kanungo et al. 2009). These methods calculate percentage of landslide area for each pixel and landslide absence. A landslide presence data layer is produced followed by the application of multivariate statistical method for reclassification of hazard for the given area. The logistic regression model, discriminant analysis, multiple regression models, conditional analysis, and artificial neural networks are commonly used for landslide mapping.

Distribution (inventory) method. The distribution (inventory) model, also known as landslide inventory, is one of the simplest approaches to landslide mapping. In this model, landslide inventory maps are produced which portray spatial and temporal patterns of landslide distribution, type of movement, rate of movement, type of displaced material (earth, debris, or rock), and others. Landslide data are obtained through field survey mapping, historical records, satellite images, and aerial photo interpretation. Landslide distribution and density maps provide the basis for other landslide susceptibility methods.

Inputs needed include slope angle, aspect and morphometry, lithology and land use, historic landslides, relative relief, land cover, and hydrological condition, among others.

Box 6.6. Tips to Select Hazard Assessment Method

Landslide hazard is different from many of the other hazards. Very few areas have frequency-volume statistics to generate a probabilistic model. However, if a probabilistic analysis exists, it should be used. On the other hand, there are several models to produce a susceptibility map, and they can be very sophisticated and data intensive. A site visit may be needed to verify some of the data. Sometimes the DEMs have a very coarse resolution and may over- or underestimate the hazard. At a minimum, slope, soils, and landcover should be assessed to determine susceptibility. If the project must be built at the base of a mountain or on a slope, a better susceptibility model should be selected.

The hazard information can also be used to get buy-in from local stakeholders. They may be shown a deterministic past event or worst-case scenario analysis, as it is easier for non-technical stakeholders to understand. The deterministic analysis can be used in conjunction with a probabilistic or susceptibility analysis to help people understand both perspectives. A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

Integration of Climate Change Considerations into the Modeling for Landslides

Another consideration will be the time horizon. The time horizon is defined as how far in the future the plan should cover. The project's lifespan should be reviewed (Step 2) to help determine the time horizon to include in the plan.

Higher precipitation intensities will affect future occurrence of landslides. While the mean rainfall for a region might not significantly change, the upper end of the distribution, and particularly the extremes, might increase markedly. The Clausius-Clapeyron rate suggests that this increase could be as large as 7 percent per degree Celsius warming for the largest events (IPCC, 2007). At the same time, changes in land use by humans affect the water infiltration rates and thus the stability of slopes. Careful consideration of both factors will be necessary to properly determine future landslide hazard.

The landslide assessment methods typically combine information on slope, soils, land cover, and hydrologic condition. Climate considerations will generally address only the changes in hydrologic condition, although secondary impacts on land cover because of climate change could be included. These consist of changes in vegetation that influence infiltration rates.

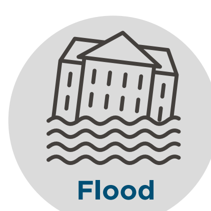
In general, the precipitation and hydrologic factors should be updated based on the climate change models, and the land cover should be updated based on how the area is expected to grow within the time horizon. Extreme rainfall characteristics are often difficult to read out of global climate models; therefore, downscaled data based on daily series might be more useful. It is important to keep in mind that statistical downscaling relies on good observations, and different methods have varying abilities to properly represent the extremes. Therefore, a validation of the series against the best available observational data should be performed before applying climate change information for future climate change risk.

The following are specific considerations for the three hazard assessment methods for landslide hazard.

Probabilistic Hazard Assessment: The hazard assessment methodology used should document whether and how it incorporates information on soil moisture or extreme precipitation events. If the method incorporates extreme precipitation events, the precipitation analysis under Riverine and Urban Flood, described below, should be used. If the method incorporates soil moisture balance, qualitative information on likely changes in soil moisture should be obtained.

Deterministic Hazard Assessment and Susceptibility Hazard Assessment: A qualitative evaluation of likely changes in soil moisture can often be obtained from a review of regional information summaries such as those provided in the IPCC reports or the World Bank Climate Change Knowledge Portal (http://sdwebx.worldbank.org/climateportal). However, the danger is that these datasets provide climatological average information (for overall trends) but they miss the frequency and intensity of wet years where landslides might be triggered. This is particularly important because that the most extreme rainfall events are expected to increase, and therefore the conditions for landslides might be triggered more readily. Output from water balance models applied to GCMs is also available from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) at https://www.isimip.org/.

6.1.4.2.8 Riverine and Urban Flood



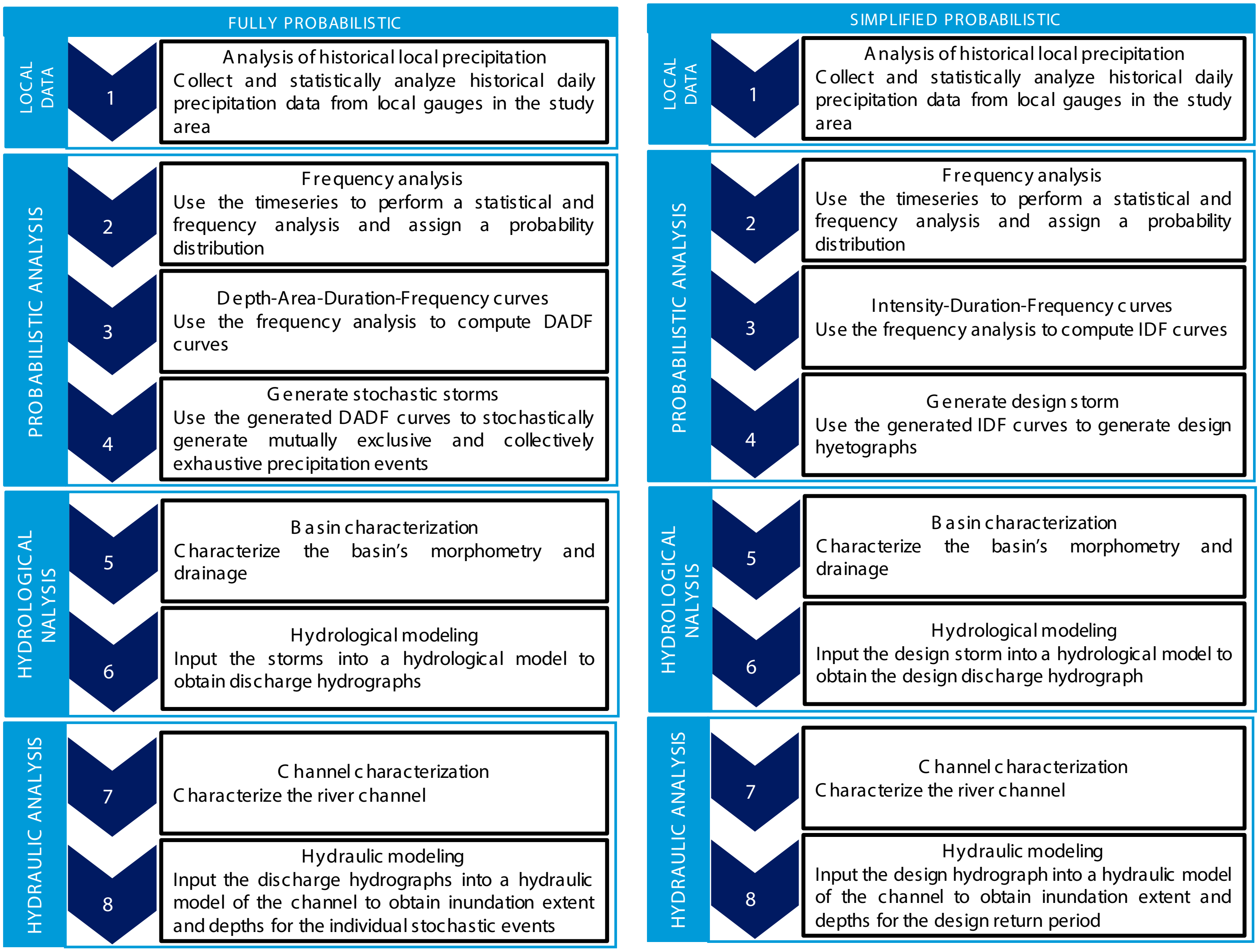
Riverine and urban floods arise through the interaction of the land surface, drainage network, and extreme precipitation events. Flood hazard analyses are usually based on analyses of extreme precipitation events and a tool (e.g., hydraulic model) to convert precipitation to flood depth. Flood hazard analyses may also be directly based on flow gauging records. The three dimensions of a hazard analysis for flooding hazard are discussed below.

- *Extent:* For riverine flooding, the inundation extent stems from a river's main channel where water overflows into the riverbanks and any further flat terrain. For urban flooding, the inundation extent comes from localized precipitation directly on the city and depends on the urban topography as well as on the city's location or impervious areas and drainage characteristics.
- *Intensity:* The intensity of flooding hazard is usually measured in terms of water (inundation) height in meters above the ground and/or flow velocity.
- *Frequency:* Floods also have an associated return period (an average of how often it can occur), with small intensities occurring very frequently and large intensities occurring very rarely. Usually engineers use water discharge values with specific return periods to design infrastructure. Additionally, a plot of intensity (e.g., water height) vs. annual rate of exceedance is called a hazard curve and is used in fully probabilistic assessments to represent the resulting intensity levels considering all possible flooding events.

Details on the application of the three hazard assessment methods (probabilistic, deterministic, and susceptibility) are described below.

Probabilistic Hazard Assessment: Probability and statistical analyses are applied to hydrological data (usually precipitation, although sometimes to discharge or streamflow) to model the frequency of recurrence of precipitation or streamflow values that are then used to model flooding. Figure 6.13 shows the basic process for both the fully and the simplified-probabilistic approaches. These two approaches are generally similar, but they differ in the probabilistic treatment of the subsequent hydrological and hydraulic modeling. In the first case (fully probabilistic), multiple flooding events (tens or hundreds) are stochastically generated (these are mutually exclusive and collectively exhaustive) covering the entire range of possibilities (including both small recurrent events and large but rare events), and these individual events are used to damage exposed assets in a risk assessment. In the second case (simplified probabilistic) a few (usually five or fewer) scenarios (no longer individual events) are modeled to represent flooding intensities with an associated return period, and these integrated hazard scenarios are used to damage exposed assets in a risk assessment. Only the first approach allows for the calculation of the accurate loss exceedance curve (LEC) from where probable maximum losses (PML) can be calculated (in addition to the average annual loss, or AAL), whereas the second approach only supports the calculation of the AAL directly, and the LEC and PML can only be estimated via extrapolation and with the assumption that the return period of the hazard is the same as that of the loss.

Figure 6.13. Basic Probabilistic Process in Flooding Hazard Modeling



Probabilistic and hydrologic analysis. Hydrologic analyses simulate natural hydrologic processes, such as precipitation, soil moisture, infiltration, exfiltration, transpiration, and storage, to estimate and route watershed or urban catchment system discharges. These analyses are typically used with observed or forecasted precipitation (rain gages and radar) to generate discharges for design storms and flood frequencies using various soil moisture conditions, rainfall, and snow cover to predict urban flooding and river responses. Statistical analyses are applied to the data (rainfall or streamflow) to evaluate extremes or peaks to determine the frequency distribution of rainfall or streamflow. This is used to evaluate specific rainfall frequency events.

Extreme events are sometimes difficult to determine when the number of years of data is insufficient (less than 30 years). To help overcome this issue, a stochastic weather simulation model, also known as a weather generator, can be used to simulate longer time periods and identify those extreme events. Two basic types of stochastic weather generators are available: the "Richardson" type (Richardson 1981; Richardson and Wright, 1984) and the "serial" type (Racsko et al., 1991; Semenov et al., 1998). Both weather generator types require initial calibration based on observed station data. In a Richardson-type weather generator (e.g., WGEN), precipitation occurrence is modeled using a first-order two-state Markov procedure, which describes two precipitation classes (i.e., wet or dry) and considers precipitation occurrence on the previous day only. More complex models might involve more than one precipitation class as well as the occurrence of precipitation on a number of days prior to the current day. One of the main criticisms of Richardson-type weather generators is their inability to adequately describe the length of wet or dry series.

The serial-type weather generator was developed to attempt to overcome problems identified with the Richardson type. The first step in the process is the modeling of the sequence of dry and wet series days. The precipitation amount and the remaining climate variables are then generated depending on the wet or dry series..

Hydraulic analysis. Hydraulic analyses simulate the fluid mechanics of the flow of water through natural or artificial channels. There are at least four approaches to model hydraulics: one-dimensional steady and unsteady flow and two-dimensional steady and unsteady flow hydraulic models. One-dimensional models assume that the velocity and depth of flows change in a single defined direction (channelized flows). Thus, they are appropriate for large river systems where most flows and velocities move in a predominant direction. The steady flow state is often used to simulate the extents (inundation and water surface elevations) of theoretical flood frequency events.[25] The unsteady flow state is often used to evaluate actual flood events or to simulate flood hydrographs created by extreme events (dam or levee breach, probable maximum flood, etc.).[26] Two-dimensional models compute the horizontal velocity components or, alternatively, the velocity vector magnitude and direction throughout the model domain, and they can be used for steady state or unsteady state evaluations.[27] These models are often used for systems that have wide floodplains, low gradients, multiple flow paths, or alluvial fan systems. Finally, statistical analyses are applied to the data (streamflow) to evaluate extremes or peaks to determine the frequency distribution of streamflow. This is used to evaluate specific flood frequency events.

Inputs needed include precipitation or streamflow time series; watershed processes that may include soil moisture, infiltration, exfiltration, transpiration, storage and precipitation; DEM; observed data; channel cross-section geometry data; and channel roughness. Specific software packages are listed in Appendix D.

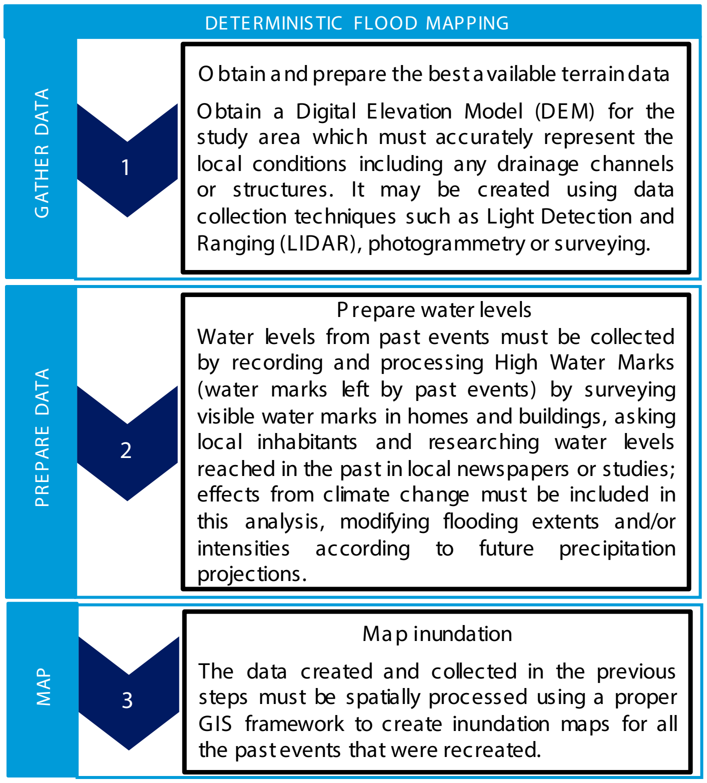
Deterministic Hazard Assessment: To conduct a past event mapping analysis, satellite imagery may be used to demarcate the extent of the flooding. This flood polygon may be used with a DEM to determine the depth of flooding. Another option involves using high-water marks, which may be captured directly after the event to help delineate the flood extent. Again, this polygon area could be used with a DEM to determine depths. High-water marks can usually be found on trees, bridges, and structures directly after an event. NOAA has structured a simple inundation mapping method and guidance, which it uses as the basis for a course on Coastal Inundation Mapping (NOAA, n.d.) and which can also be applied to riverine or urban flooding. For details on this method, see NOAA's Mapping Coastal Inundation Primer (NOAA, 2012). This method consists of three steps, as outlined in Figure 6.14:

25 Steady flow models assume a constant discharge over time. Since they not account for attenuation of discharges due to storage and timing effects, they tend to calculate more conservative (higher) water surface elevations than an unsteady model with the same geometry and parameters (Manning's "n", coefficients, etc.).

26 Unsteady flow models route a hydrograph (or multiple hydrographs) through the hydraulic system using geometry and parameters (Manning's "n", coefficients, etc.). These models account for attenuation of discharges and the timing of contributing and converging drainage areas.

27 The discussions of steady and unsteady flow models for one-dimensional models applies to these models as well.

Figure 6.14. Flood Mapping Process



For a modeled past event, if the water level or flow was captured by a river gauge, then the hydrologic and hydraulics models described above (for PHA) could be used with specific water level values and flows to derive a floodplain for the single event. For a modeled worst-case event, these models could be run with assumptions for the hydrologic parameters, surface roughness, and using a coarser DEM for channel geometries for an event. A flood modeling specialist should be consulted to determine appropriate assumptions based on the region. Inputs needed include, for a past event mapping analysis, satellite imagery of the flood and digital elevation model, river gauge flow or height value and high-water marks collected as points on a map. For past and modeled events, inputs may include watershed processes which may include soil moisture, infiltration, exfiltration, transpiration, storage and precipitation, DEM, observed data, channel cross-section geometry data and channel roughness.

Susceptibility Hazard Assessment: The last approach is to develop a simple susceptibility map using a DEM, river location, soils (if available), and land cover. The riverine floodplain will often consist of softer soils which can be seen on a soils map, while urban flooding could be supported by identifying the impervious areas in the city. Areas with a lower elevation would be more likely to be flooded and would be designated on the map. These designated areas would not be associated with a return period interval. Inputs needed include DEM, river location, soils (if available) and land cover for riverine flooding, and identification of impervious areas and drainage system for urban flooding.

***Historical Timeline Analysis:** The last option, which applies only to the agriculture sector, is the simple method used in the Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners developed by the World Bank (2016). Within this risk approach, the hazard component is treated implicitly through the construction of a timeline of past events. This timeline of past natural hazard events is constructed for the longest time period possible (and it should be the same window of time as the agricultural production timeline to be built) and includes only flooding events to determine average annual losses due to this hazard. However, a multi-hazard risk assessment may be done as well, in which case all types of hydrometeorological hazards (droughts, extreme temperatures, hurricanes) can be included in the timeline. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section below for details on the risk calculation.

Box 6.7. Tips to Select Hazard Assessment Method

To perform an analysis on a group or portfolio of assets in a large area where it may be difficult to analyze each one in detail and the capture of intricacies or specific and very localized effects (such as erosion) is not required, then a fully probabilistic approach may be more appropriate. In any case, if a probabilistic analysis was already conducted for the project area, it should be used, an additional analysis may be needed to see how the project will impact the floodplain. It is necessary to know what areas and which project components could be flooded, and if the project is sited in a floodway (an area of the floodplain which is effective in carrying flow), it should be moved if possible.

If the project is designing or rehabilitating near a river or in an urban environment and a high level of detail is needed, a simplified probabilistic or deterministic approach may be more appropriate. It will be necessary to know exactly which project components could be flooded, by how much floodwater, and how much flow velocity will act on the structure. If the project is sited in a floodway (an area of the floodplain which is effective in carrying flow), it should be moved if possible. These approaches will provide more detailed hazard analysis. If hazard recurrence plays an important role, a simplifiedprobabilistic approach should be used. Otherwise, if uncertainty or hazard recurrence is not a major determinant of the hazard, a deterministic approach should be used.

Moreover, some of the flood models require a great deal of data, which may not be available for the region. If the data needed to run a fully or simplifiedprobabilistic analysis are not available, the existence of flood mapping expertise in the area should be determined, and a deterministic approach of recreating or modeling past events or worst-case scenarios should be used. The information provided by a deterministic assessment can also be used to get buy-in from local stakeholders, who should be shown a deterministic past event or worst-case scenario to help influence where the project should be sited. A deterministic assessment is easier for non-technical stakeholders to understand. The deterministic assessment can be used in conjunction with a probabilistic analysis to help people understand both perspectives. A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

Integration of Climate Change Considerations into the Modeling for Riverine or Urban Flood

Another consideration is the time horizon, or how far in the future the plan should cover. The project's lifespan (Step 2) should be reviewed to help determine the horizon to be planned for.

The primary climate change consideration for flood will generally be precipitation IDF. Climate change considerations that impact commonly used hydrologic, statistical, and hydraulic models include changes in precipitation (amounts, distribution, and intensities), temperature, land use (to determine runoff characteristics), evapotranspiration, vegetation, and sea level. These changes can be incorporated into the models. These parameters can be direct inputs into the models (precipitation, streamflow, etc.) or they can be used to estimate parameters (i.e., temperature change on farming and land use changes).

GCMs typically provide model output at a monthly time step and a broad spatial scale that is not directly relevant for flood modeling. If RCMs exists for the project area, these should be used in lieu of GCMs. However, downscaling methods should still be used to convert coarse GCM or RCM output to a daily time step at a more localized spatial scale. Global daily downscaled climate projections are now available from NASA at https://cds.nccs.nasa.gov/nex-gddp/. These statistically downscaled products require validation for local conditions, where possible. This is particularly the case for the more extreme part of the distribution of daily values. The reason for this uncertainty is connected to the methods used for downscaling, each of which might have been based on different objectives. The weather generators discussed above can be used to input the changes in likelihoods and intensities of the extremes due to climate change to obtain modified time series of climate variables. Recommended downscaling weather generators include the non-parametric K-Nearest Neighbor[28] (Simonovic and Peck, 2009) or SDSM[29] (Wilby and Dawson, s.f.)

If there is a limitation for the use of weather generators, the Clausius-Clapeyron relationship of 7 percent increase per 1-degree Celsius of "potential" water carrying capacity provides a general estimate of how effects from warming might be included, though structural changes in weather patterns might also affect the distributions.

Specific considerations for the three hazard assessment methods discussed below.

Probabilistic Hazard Assessment:

1. The climate change analysis approach should be aligned with the flood hazard method. Critical precipitation events may have been determined in various ways. Where there are reliable long-term precipitation monitoring sufficient to establish precipitation IDF, or DADF curves may be created. On the other hand, this might not be the case for some locations, so the hydrology might be determined by, for example, extrapolation from a similar location with good precipitation records, from climate modeling, or from generalized published IDF curves for the region. The climate analysis should be consistent with the underlying method for evaluating flood hazard under current conditions.

2. Estimates should be conducted of how climate change might influence the distribution of rainfall, particularly extreme rainfall, and adjust the previously determined IDF or DADF curves or return periods (while mean precipitation might not change much, the tails, or extremes, of the distribution quite likely will increase). The following approaches may be used:

   - Where detailed rainfall data and statistics are available along with downscaled climate model output, formal statistical methods should be used to modify historic time series to represent future projections from climate change (such as the statistical downscaling weather generators mentioned above), or present-day IDF curves (expressed as an extreme value distribution) should be converted to future IDF curves based on the relative change in downscaled climate model output between the future period of interest and the same model hindcast for recent decades). When applying these changes, another factor that might perturb statistical relationships (aside from the projected changes in variables such as precipitation) is changes in the watershed and runoff channels over time. Often, building of infrastructure has increased runoff speed and reduced infiltration capacity, leading to more water available for flooding than before.

   - Another approach that can be considered is a space-for-time substitution. This option is applicable if it has been determined that the future climate at the location of interest will resemble the current climate at a location for which IDF curves have been developed.

   - Finally, predictions of changes in extreme precipitation events as provided by GCMs have been assembled by year and geographic location by the Expert Team on Climate Change Detection and Indices (Sillmann et al., 2013a; 2013b) and served as CLIMDEX by Environment Canada (http://www.cccma.ec.gc.ca/data/climdex/climdex.shtml). These indices are useful but might need to be augmented by extreme-value statistical analyses of the underlying daily data (hydrologically important hourly data is hardly ever accessible, and therefore daily data might be the most realistic target for analysis).

28 https://ir.lib.uwo.ca/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1027&context=wrrr

29 http://www.lboro.ac.uk/departments/sspgs/social-impact/climate-adaptation/

Regardless of the approach, the analysis of change should account for the time associated with flood development. For local urban flooding, the analysis can assume that the change in flood risk is directly related to the change in daily or sub-daily precipitation. For flood hazard along a major river with a large time of concentration, the risk may be more closely tied to multi-day cumulative (e.g., 5-day), weekly, monthly, or even seasonal precipitation totals.

3. The baseline hazard assessment (hydrologic and hydrauº analyses) should be re-run using modified inputs based on future climate.

   Uncertainty in parameters impacted by climate change is typically accounted for using a sensitivity analysis. This means evaluating the hydrologic model using the 10 percent, 50 percent, and 90 percent confidence intervals of modeled variables impacted by climate change. Modeled trends for hydrologic parameters associated with climate change often have high variability between the 10 percent and 90 percent confidence intervals. As such, the sensitivity analysis of the hydrologic model will reflect the impacts of this variability on watershed responses. Selecting observation stations and checking the actual trends in recorded data versus previously modeled trends will assist in verifying the trend. Thus, the hydrologic model can be used to evaluate past climate change models with actual observations. It is important to compare actual processes with modeled processes and hindcasting (comparing previous climate change models to observed data). This provides valuable information on trend lines and their veracity. This is important because multiple climate change models produce multiple results in the same watershed.

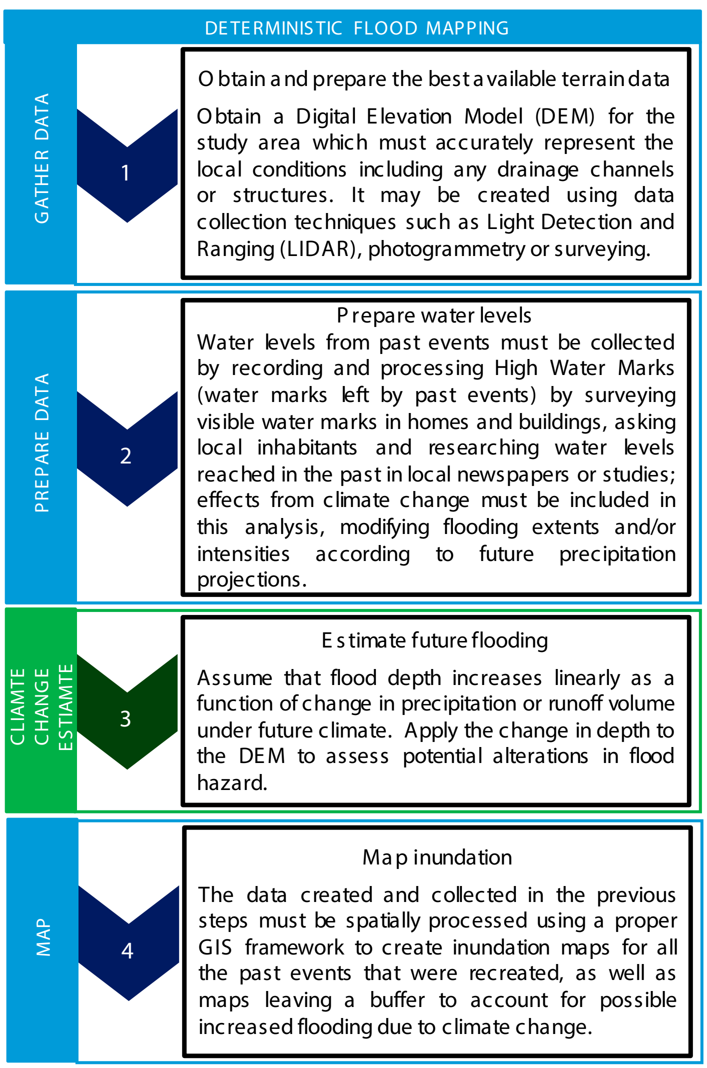
   Climate change considerations are fed into hydraulic models through hydrologic (and statistical) modeling, as discussed above. Many communities prepare a suite of mapping/analyses for present conditions and multiple future scenarios. This allows staged implementation (using projected dates or thresholds) and an adaptive management approach to mitigation measures. It provides the affected communities with a decision support tool to select the appropriate level of protection or the proper mitigation measure depending on the time frame and location of the asset.

Data needed include statistics or future projected time series of precipitation and/or runoff for critical maximum events. Figure 6.15 summarizes the probabilistic hazard assessment process for flood hazard incorporating climate change.

Figure 6.15. Probabilistic Flood Modelling Incorporating Climate Change

Deterministic Hazard Assessment: For a modeled event (past or worst-case), the same considerations as those applied for the PHA should be applied but aligned with and limited to the simplifications and assumptions made by the hazard assessment method. For past-event mapping analysis, a buffer should be added to the delineated areas based on future precipitation amounts and after consulting local flood experts. It should be assumed that flood depth increases linearly as a function of change in precipitation or runoff volume under future climate. The change should be applied in depth to the DEM to assess potential alterations in flood hazard. Figure 6.16 shows how to incorporate climate change into the flood mapping process. Data needed include changes in future precipitation volume, particularly extreme rainfall events.

Figure 6.16. Flood Mapping Incorporating Climate Change



Susceptibility Hazard Assessment: A buffer should be added to the delineated areas based on future precipitation amounts and after consulting local flood experts. It should be assumed that flood depth increases linearly as a function of change in precipitation or runoff volume under future climate. Apply the change in depth to the DEM to assess potential alterations in flood hazard. Data needed include changes in future precipitation volume, particularly extreme rainfall events.

6.1.4.2.9 Volcano

The three dimensions of a hazard analysis for volcanic hazard are discussed below.

- *Extent:* Volcanic hazard can both local and regional, depending on the type of sub-hazard considered. For example, lava flows or lahars tend to have smaller or limited spatial extents when compared to the extent of, for example, ashfall, which can extend hundreds of kilometers. Special consideration should be given to the type of sub-hazard to analyze.

- *Intensity:* Like extent, the intensity measure will vary according to the type of sub-hazard considered. For lahar/mud/pyroclastic flows, the most common intensity measure is the lahar/mud/pyroclastic flow depth, whereas for ashfall the most common intensity measure is maximum ash load in kg/m^2.

- *Frequency:* Each sub-hazard also has an associated return period (an average of how often it can occur), with small intensities occurring very frequently and large intensities occurring very rarely. A plot of intensity (e.g., ash load) versus annual rate of exceedance, called a hazard curve, is used in fully probabilistic assessments to represent the resulting intensity levels considering all possible events. For ashfall, very large return periods (i.e., up to 10 million years) are used in a volcanic hazard assessment because of the especially low rates of recurrence of explosive volcanic eruptions.

Details on the application of the three hazard assessment methods (probabilistic, deterministic and susceptibility) are described below. Appendix D contains specific models.

Probabilistic Hazard Assessment: Volcanic hazard has at least three expressions: lava flows, ashfall, and lahar (or pyroclastic) flows. Modeling of each type of hazard is described below.

- *Lava Flow Model.* Probabilistic modeling of lava flow hazard is a two-stage process. The first step is an estimation of the possible locations of future eruptive vents followed by an estimation of probable areas of inundation by lava flows issuing from these vents. *First, the location of the lava flow source is sampled from a spatial density model of new, potentially eruptive vents. Second, the model simulates the effusion of lava from this vent based on field measurements of thicknesses and volumes of previously erupted lava flows within an area encompassing the site of interest. The simulated lava flows follow the topography, represented by a DEM. Given the input data, Monte Carlo simulations generate many possible vent locations and many possible lava flows, from which the conditional probability of site inundation by lava flow, given the opening of a new vent, is estimated. Inputs needed include spatial distribution of past eruptive vents, the distribution of past lava flows within an area surrounding the site, and measurable lava flow features, including thickness, length, volume, and area, for previously erupted lava flows.*

- *Ash Model. Probabilistic ash models have four processes. Volcanic sources with respect to any given site of interest must be identified. For each volcanic source the annual eruption probability is calculated based on magnitude-frequency relationships of past events. Then, a set of stochastic events and volcanic ash load attenuation relationships must be calculated (using an ash dispersal model). Next, a calculation of the annual exceedance probability of the volcanic ash hazard for each stochastic event at each project site is conducted. Geoscience Australia developed a volcanic ashfall model for the Global Assessment Report 2015 (GAR 15) using the Probabilistic Volcanic Hazard Assessment (PVHA) methodology and the VAPAHR tool (Bear-Crozier et al., 2014). See GVM and IAVCEI (2015) and Cardona et al. (2015) for details on this model. Inputs needed include appropriate ash load attenuation function, hazard characterization, and predictive relationship.*

- *Lahar Flows.* Large landslides and debris flows, or lahars, pose some of the greatest threats to people and property downstream from stratovolcanoes.

Deterministic Hazard Assessment: To conduct a past-event analysis, it is necessary to determine whether volcano lava flow, ash field, and lahar flows from previous events have been mapped near the project site. Universities, the USGS, and other organizations may develop volcano hazard maps after an event. Inputs needed include location, digital elevation model and amounts of lava flows, lahar flows, or ashfall to recreate a past event, and location, digital elevation model and thickness, length, volume, and area for lava and lahar flows and an ash load attenuation function to model a worst-case event.

Susceptibility Hazard Assessment: The last approach is to develop a simple susceptibility map using volcanic soils data, low elevation areas near a volcano, and previous known hazard areas. These designated areas would not be associated with a return period interval. Inputs needed include volcanic soils data, low elevation areas near a volcano, and previous known hazard areas.

Box 6.8. Tips to Select Hazard Assessment Method

To perform an analysis on a group or portfolio of assets in a large area where it may be difficult to analyze each one in detail and the capture of intricacies or specific and very localized effects is not required, a fully probabilistic approach may be more appropriate. In any case, if a probabilistic analysis was already conducted for your project area, it should be used. Since volcano hazard consists of several hazards, it should be determined whether one, two, or three hazards are applicable and should be addressed.

If individual infrastructure is being designed or rehabilitated adjacent to an active volcano and a high level of detail is needed, a simplified probabilistic or deterministic approach may be more appropriate. It will be necessary to know exactly which project components are exposed to potential lava flows, lahars, and ash. These approaches will provide more detailed hazard analysis. If hazard recurrence plays an important role, a simplified probabilistic approach should be used. Otherwise, if uncertainty or hazard recurrence is not a major determinant of the hazard, a deterministic approach should be used.

Moreover, some volcano models require a great deal of data which may not be available for the region. If the data needed to run a fully or simplified probabilistic analysis are not available, a deterministic approach should be used. The information provided by a deterministic assessment can also be used to get buy-in from local stakeholders, who should be shown a deterministic past event or worst-case scenario to help influence the siting of the project. A deterministic assessment is easier for non-technical stakeholders to understand. The deterministic can be used in conjunction with a probabilistic analysis to help people understand both perspectives. A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

6.1.4.2.10 Wildfire

The following are the three dimensions of a hazard analysis for wildfire hazard.

- *Extent:* Wildfire hazard can be both local and regional, depending on the extent and availability of fuel material. For example, local fires occur very frequently in urban settings, but large fires have also occurred in vast areas with a lot of natural vegetation, such as the California wildfires of 2018. Special thought should be given to the characteristics of the study area.

- *Intensity:* Flame length.

- *Frequency:* Likelihood is often estimated statistically from previous events in the region, but it can also be modeled.

Details on the application of the three hazard assessment methods (probabilistic, deterministic, and susceptibility) are described next. Appendix D provides information on specific software packages.

Probabilistic Hazard Assessment: Probabilistic models are rare for wildfire hazard due to their complexity, especially fully probabilistic ones where stochastic scenarios are generated. However, a simplified probabilistic analysis may be used. Modeling intensity often relies on wildfire behavior models. Models for predicting surface and crown fire rates of spread (e.g., Forestry Canada Fire Danger Group, 1992; Rothermel 1972, 1991), crown fire transition and propagation (Scott and Reinhardt, 2001; Van Wagner 1977, 1993), and a host of potential fire effects (e.g., tree mortality, fuel consumption, smoke emissions, soil heating, and erosion) may be used to predict intensity. Likelihood is often estimated statistically from ignition data or simulated with fire behavior models. Thus, a time series of wildfire events is needed. Wildfire likelihood can be represented as either ignition probability or burn probability. Typically, ignition probability is statistically modeled using fire occurrence data, whereas burn probability is estimated via simulation. The two representations can exhibit vastly different spatial patterns and tend to be used for different purposes. For example, estimates of ignition probability are used in initial ignition simulations, and burn probabilities are more often applied in fuels management planning problems. Inputs needed include data on fuels, winds, meteorology, DEM, vegetation, and trees to model intensity, and time series of wildfire events to model likelihood.

Deterministic Hazard Assessment: To conduct a past event analysis historical data of the location and intensity of the wildfire event are used to see if previous burn areas have been mapped in or near the project site, including reviewing historic satellite imagery. Universities and other organizations sometimes develop burn maps after an event. To conduct a modeled event analysis, fuel source locations can be mapped to help determine where fires may occur in a locational model. Some long-term records can be derived from tree ring data, which help to determine if typical recurrence intervals might be present. Input data needed include location, intensity and satellite imagery of a historic event to conduct a past-event analysis, and data on fuels, winds, meteorology, DEM, satellite imagery, vegetation and trees to model a worst-case event.

Susceptibility Hazard Assessment: The last approach is to develop a simple susceptibility map using different data including fuel sources. These designated areas would not be associated with a return period interval. Input data needed include data on fuel sources.

Box 6.9. Tips to Select A Hazard Assessment Method

To perform an analysis on a group or portfolio of assets in a large area where it may be difficult to analyze each one in detail and the capture of intricacies or specific and very localized effects is not required, then a fully probabilistic approach may be more appropriate. In any case, if a probabilistic analysis was already conducted for your project area, it should be used.

If designing or rehabilitating individual infrastructure in or adjacent to a forest and a high level of detail is needed, a simplified probabilistic or deterministic approach may be more appropriate. It will be necessary to know exactly which project components are exposed to potential wildfires. These approaches will provide more detailed hazard analysis. If hazard recurrence plays an important role, a simplified probabilistic approach should be used. Otherwise, if uncertainty or hazard recurrence is not a major determinant of the hazard, a deterministic approach should be used.

Moreover, some of the wildfire models require a great deal of data which may not be available for the region. If the data needed to run a fully or simplified probabilistic analysis is not available, a deterministic approach should be used. The information provided by a deterministic assessment can also be used to get buy-in from local stakeholders, who should be shown a deterministic past event or worst-case scenario to help influence the siting of the project. A deterministic assessment is easier for non-technical stakeholders to understand. The deterministic can be used in conjunction with a probabilistic analysis to help people understand both perspectives. A susceptibility map is appropriate to identify susceptible populations and non-project buildings and infrastructure to help determine community impacts.

Integration of Climate Change Considerations into the Modeling for Wildfire

As the climate warms, moisture and precipitation levels are changing, with wet areas often becoming wetter and dry areas tending to become drier. Higher temperatures and earlier spring snow-melt typically cause soils to be drier for longer, increasing the likelihood of drought and a longer wildfire season. These hot, dry conditions also increase the likelihood that, once wildfires are started by lightning strikes or human error, they will be more intense and longer-burning.

Wildfire hazard is likely to increase if temperature rises and soil moisture decreases, although the connections between climate and wildfire are complex. For example, a dry year following a wet year might be particularly conducive to fire, as the wet year has resulted in build-up of sufficient fuel load which can then ignite during the subsequent dry period . Relatively dry conditions can also prepare the area for higher sensitivity if a short-lived but intense heat wave occurs. Similarly, in mountain environments, dry downslope winds can very quickly raise the fire danger. Therefore, depending on location, different drought and wind conditions may need to be considered to estimate the fire danger. Climate change may also result in substantial changes in land cover and associated fire fuel. Other factors such as harvest practices, fire suppression, and fuel management are also likely to be important in determining future fire risk. Therefore, climate considerations for wildfire should be made explicit only when a scientific study relevant to the area of interest is available.

As with drought, wildfire occurrence depends on dry conditions. Meteorological perspectives based solely on precipitation might be useful in the near term, but as temperatures rise, the influence of temperature on the water balance might become increasingly important. While clearly influencing the fire regime, the actual estimation of temperature-enhanced evapotranspiration is difficult, and the different formulations vary quite strongly in their sensitivity to the underlying temperature changes.

Another aspect of the warming world is that both dynamically and through local feedbacks the year-to-year variability is likely to increase. Therefore, while the long-term averages might remain fairly stable, larger amplitude variability would lead to enhanced wildfires during the dry years as the duration and intensity of the dry conditions are enhanced.

The following are specific considerations for the three hazard assessment methods.

Probabilistic Hazard Assessment and Deterministic Hazard Assessment: The models should be updated when they are using evapotranspiration, temperature, precipitation, and land cover. The wildfire season will be extended. A baseline season should be identified using historical data, the percentage of time should be determined, and the likelihood should be added to reflect this change. The likelihood needs to explicitly look at interannual variability and therefore model sequences based on timeseries, not climatological average products.

There are many different approaches to estimate fire danger and incorporate the climate-vegetation-fire interactions and feedback (see Harris et al., 2016 for an overview). The Canadian Forest Fire Danger Rating System (CFFDRS) contains the Fire Weather Index (FWI) and the Fire Behavior Prediction System (FBPS) (Natural Resources Canada, n.d.). A recent update by Wang et al. (2017) can be found as an R-package (CFFDRS: https://r-forge.r-project.org/projects/cffdrs/). Data needed include the likelihood of dry conditions, which can be estimated from precipitation records, and more detailed drought indices based primarily on monthly data.

Susceptibility Hazard Assessment: How lower moisture content, higher temperatures, and less precipitation impact the susceptible areas should be determined.

6.1.4.3 Quantification of the exposure component

The exposure module of a Disaster and Climate Change Risk Assessment consists of a geo-referenced database containing all of the physical assets, as well as population, that may be affected by a natural hazard. The hazard module (detailed above) will affect what is contained in this module. Depending on the project, it may include one or more (i) buildings (residential, commercial, institutional or industrial buildings); (ii) specialized infrastructure such as ports, roads, water and sanitation systems, and others; and (iii) people.

This module must properly characterize the assets, storing attributes such as their typology, physical conditions, construction types and materials, number of stories, use sector (for buildings), economic value, and any others that may be needed to connect to the vulnerability module (see the Quantification of the Vulnerability Component section to identify specific characteristics).

One of the most important attributes is the economic value, since the risk assessment will use this value to quantify the economic losses to the exposed elements. Ideally this valuation should include the physical reposition value of the structure (i.e., what it would cost to replace or restore the element to its original state. Note that this does not include the value of the land, nor is it the market value of the property.), the value of its contents (permanent equipment, architectural elements, etc.), and the economic value generated by its functionality or operation. This is needed since the risk calculation should, similarly, compute direct losses to the structure and its contents and indirect losses due to loss of functionality. Information on the employees (and other occupants) and any business information should be collected: monthly rental, owner income per day, employee wages per day, and number of employees and/or occupants during the day and night. Because the second and third aspects can sometimes be difficult to evaluate, usually only the first aspect is used, and thus only direct losses are calculated. Where possible, efforts should be made to gather all three.

Depending on the type of project, there may be only one or a few assets (e.g., a single road with a few bridges), or there may be multiple assets (e.g., hundreds or thousands of buildings in a city) that require characterization. Corresponding with the quantity of assets and the level of detail needed, there are two approaches to gather data and construct the exposure, as seen in Table 6.4. To build the exposure of the project, either of these two approaches may be used. To build the exposure of nearby communities and third parties, the aggregated approach should be used.

Table 6.4 Approaches to Building the Exposure

<table>
<tr><th>Method</th><th colspan="2">Description</th></tr>
<tr><td>Detailed - individual assets</td><td colspan="2">This approach should be used for individual assets that require a detailed risk assessment. Information on the physical characteristics of the asset may come from design documents, as-builts, or structural drawings. Detailed business information may be obtained to determine operational interruption losses, and employee data may be obtained to help determine social losses. Surveys may be conducted using ground personnel.</td></tr>
<tr><td rowspan="2">Proxy - aggregated assets</td><td rowspan="2">This approach should be used for groups of assets that do not require an individualized detailed risk assessment. An aggregate-level analysis means that the characterization of assets is done by grouping typologies. Information on the physical characteristics of the asset may come from satellite imagery and existing secondary data such as surveys and censuses. Business information may be approximated using business square footage and local business parameter data. The exposed population may also be estimated with square footage. Contents may be approximated based on the occupancy of the structure: residential is usually ½x the structure value; commercial, industrial, and agricultural is usually 1x structure value; and schools and hospitals are usually 2x structure value. This approach should be used to assess communities in or near the project area (to evaluate risk exacerbation to third parties).</td><td>Spatial individualization: Even though the assets are grouped by typologies, individual assets (e.g., building by building) are still identified and assigned a typology.</td></tr>
<tr><td>Spatial aggregation: In addition to grouping assets by typology, assets are further aggregated spatially to a larger level such as a city block. The grouping unit will have a single characteristic representing the most common characteristics of the individual assets it contains.</td></tr>
</table>

Usually, an exposure mapping exercise is conducted where a comprehensive depiction of the physical environment of the project intervention areas and the project's zone of influence is made. In this exercise, all of the characteristics of the exposed elements are visualized and analyzed to find patterns, trends or, in general, to get an overview of what is exposed to natural hazards in terms of types of infrastructures, overall dimensions, values, geographical distribution, and other specifics.

6.1.4.4 Quantification of the vulnerability component

Quantification of vulnerability aims to assess more precisely a project's innate propensity to suffer damages when facing a natural hazard. This means, in general and for all hazards, studying the inherent characteristics of exposed structures and people that make them more or less resistant to the demands imposed by natural hazards.

Because the risk can be assessed for both economic losses (which are mainly due to structural damage) and loss of life, the vulnerability of both physical assets and people is included here. For purposes of this document, the term "structural vulnerability" refers to the former and the term "social vulnerability" refers to the latter.

6.1.4.4.1 General vulnerability assessment considerations

Since the vulnerability module links the hazard and exposure modules, the methods for evaluation of vulnerability must have correspondence to both. This section will provide guidance on selecting a vulnerability assessment approach. Table 6.5 summarizes the two basic kinds of vulnerability assessments.

It is important to evaluate a project's vulnerability not only structurally via its design, but also its vulnerability during the construction phase and the operational phase of the project. A simple exposure assessment is recommended for the construction phase.

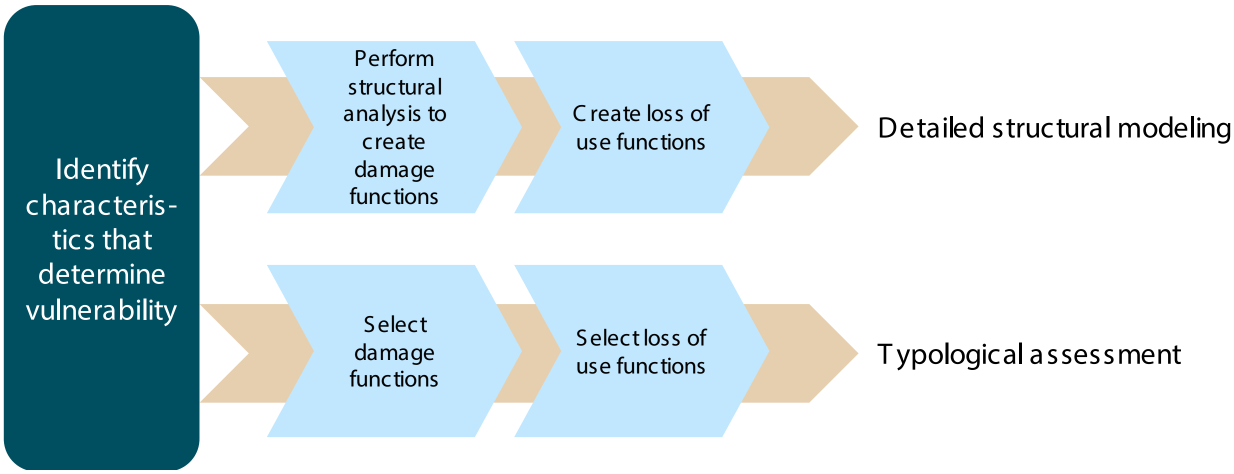
Table 6.5. Vulnerability Assessment Approaches

<table>
<tr><th>Method</th><th colspan="2">Description</th></tr>
<tr><td rowspan="2">Detailed structural modeling - individual assets</td><td rowspan="2">Design documents, as-builts, structural drawings, site elevations, and site inspections from a technical specialist (e.g., structural engineer or similar) are used to create vulnerability and/or fragility functions specifically for the structure. This entails performing structural analyses following standard engineering methods to model a structure's performance under varying loading demands from natural hazards.
This approach should be used in conjunction with the Detailed – Individual Assets approach for the exposure. General sample surveys are found in Appendix E.</td><td>Probabilistic: To conduct a probabilistic risk assessment, in addition to the hazard needing to be probabilistic, the vulnerability needs to be treated probabilistically. Probabilistic structural analysis entails formulating a mathematical model representing the probability that the structure behaves in a certain way given that its properties and the actions on the structure are of a random or incompletely known nature (Ditlevsen and Madsen, 2005). Probabilistic approaches such as structural reliability analysis, the Hazus fragility approach, or the CAPRA vulnerability approach may be used (details on these are given in this section). In general, these approaches aim to incorporate the uncertainties in engineering in a manner that allows probabilities (and thus the various statistical moments) of damage and failure and ultimately, risk, to be estimated.
This approach can be used in conjunction with the probabilistic (fully probabilistic or simplified probabilistic) or deterministic (past-event or worst-case) approaches for the hazard.</td></tr>
<tr><td>Deterministic: Deterministic structural analysis entails formulating a mathematical model representing the behavior of a structure when all its properties and actions on the structure are uniquely given (Ditlevsen and Madsen, 2005). This means performing a structural analysis to determine the resulting performance and damages for a corresponding solicitation without considering any uncertainty.
This approach can be used in conjunction with the deterministic (past-event or worst-case) approach for the hazard.</td></tr>
<tr><td rowspan="2">Typological assessment - multiple assets</td><td rowspan="2">Existing (in literature) vulnerability and/or fragility functions based on general building typology or building occupancy may be used and assigned to assets.
This approach should be used in conjunction with the Proxy – Aggregated Assets approach of the exposure and should be used to assess the risk for communities in or near the project area (to evaluate risk exacerbation to third parties). General sample surveys may be found in Appendix E.</td><td>Probabilistic: Fragility and vulnerability curves are probabilistic per se. However, care should be taken with vulnerability curves, making sure that the selected functions explicitly consider uncertainty through at least the first two statistical moments and that both of these are used (sometimes only the mean values are taken).
This approach can be used in conjunction with the probabilistic (fully probabilistic or simplified probabilistic) or deterministic (past-event or worst-case) approaches for the hazard.</td></tr>
<tr><td>Deterministic: Mean values of vulnerability and/or fragility functions are used without considering uncertainty.
This approach can be used in conjunction with the deterministic (past-event or worst-case) approach for the hazard.</td></tr>
<tr><td>*Historical timeline analysis[30]</td><td colspan="2">For the special case of the agriculture sector and the historic timeline risk analysis, the vulnerability component within this approach is implicit in the establishment of a correlation between the occurrence of a hazard and a decrease in production (losses) in the timelines. Consequently, there is no explicit vulnerability procedure for this case.</td></tr>
</table>

30 This type of analysis is a simplified risk assessment method used specifically for the agriculture sector. This method is treated as a special case in this Methodology given that more detailed disaster risk models for the agricultural sector are still very new and under development; hence, the other more standardized approaches detailed in this Methodology for the hazard, exposure, and vulnerability components do not necessarily always apply to this sector.

The activities that comprise each of the two approaches (detailed structural modeling for individual assets and typological assessment for multiple assets) are summarized in Figure 6.17.

Figure 6.17. Summary of Activities to Develop a Vulnerability Assessment



Detailed Structural Modeling

This approach requires detailed information on the project component(s) to be evaluated. This information may come from design documents, as-builts, structural drawings, and site elevations. It should also include a site inspection from a technical specialist (e.g., structural engineer or similar). Project-specific vulnerability functions are created and used to generate loss estimates. The process to create these functions consists of three activities: (1) identify specific characteristics that determine vulnerability, (2) perform a structural analysis to create vulnerability functions, and (3) create loss of use functions.

1. Identify specific characteristics that determine vulnerability:

   For proposed buildings and infrastructure, characteristics may be collected from design documents and through calls with the designer and developer. For existing buildings and infrastructure, an engineer may be needed to inspect the site and complete a survey. The specific characteristics required are provided by hazard type in the following section on Hazard-Specific Vulnerability Considerations. These include how the buildings were constructed, the materials used, and key aspects that make them more or less vulnerable to the specific hazard.

2. Perform a structural analysis to create damage functions:

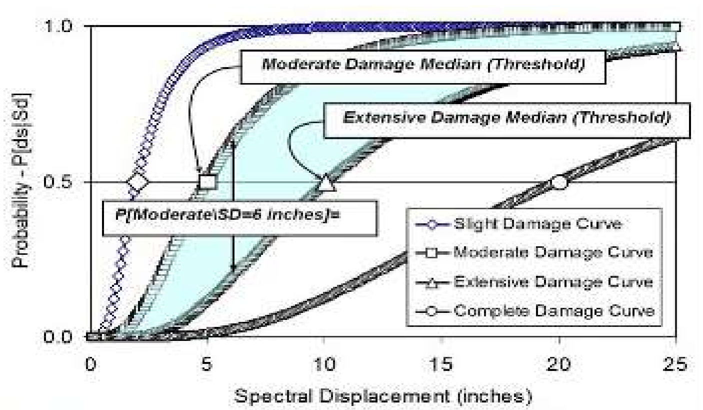
   Detailed structural analyses must be conducted to evaluate and test the response and performance of a structure with respect to the loading demands imposed on it by natural hazards. Specific structural analysis methods exist for solicitations coming from different hazards, but in general these analyses involve either analytically or empirically modeling the behavior of the structure under these solicitations, in terms of how and to what extent it can be damaged. Standardized methods exist to model the response of a structure and corresponding vulnerability mainly to seismic, wind, and water loads, as is reflected, for example, in the ASCE/SEI 7 building standard (see ASCE/SEI 7-16 (ASCE, 2016) and ASCE/SEI 7-10 (ASCE, 2010)) and the many other national and local building standards developed by individual countries. To integrate this structural analysis to a risk assessment, one more step must be taken: translating the detailed structural indicators obtained from the analysis into a more global measure (in terms of a structure as a whole) that allows a broader and more understandable quantification of damage. To do this, three main approaches can be used: applying structural reliability theory, using the Hazus approach of generating fragility curves (FEMA, n.d.), and using the CAPRA approach of generating vulnerability curves (ERN-AL, n.d. a; ERN-AL, n.d. f; Cardona et al., 2015; Ordaz, 2000).

For a probabilistic treatment of the vulnerability component (to be used in a probabilistic risk assessment and using a corresponding probabilistic hazard assessment and the detailed individual asset exposure approach), any of the three approaches provide the required probabilistic treatment.

a) Structural reliability is "a system's ability to perform an intended function without any disruption; mathematically speaking, reliability is a measure that equals probability of no failure" (Mohammadi, 2013: 2) and it came up as a way to acknowledge and treat uncertainty in engineering problems, including those investigating a structure's failure, in a rigorous way. In this first approach, structural reliability theory is applied to the detailed structural analyses mentioned above to ultimately calculate probabilities of failure or collapse of a structure or system (see Franchin et al., 2012; Lazar and Dolsek, 2012; Todinov, 2008; Wayan, 2012). Johansson et al., (2013) makes an interesting analysis and comparison of the reliability and vulnerability concepts for critical infrastructure, acknowledging their core similarities and also their different nuances. Basically, it highlights the importance of considering and analyzing both an entity's ability to perform its intended function and its inability to withstand strains.

b) FEMA (the Federal Emergency Management Agency of the United States) developed its own system and methodology to evaluate losses from disasters, called Hazus (FEMA, n.d.). The Hazus vulnerability module entails determining the probability of a structure being in a specified damage state. The response of a structure to a wide range of solicitations is expressed through fragility curves, which provide these probabilities. The process to construct these curves consists of, first, obtaining the maximum response of the structure, second, calculating the probability of being or exceeding each damage state, and third, computing the probability of being exactly in each damage state. For the first step, a structural analysis is conducted using any of the abovementioned methods. In the second step, damage states (i.e., five discrete categories representing the extent of damage: none, slight, moderate, extensive and complete damage) are defined, threshold values of the selected measure of intensity of the hazard are associated with each damage state, and they are then treated as a random variable following a log-normal distribution. The resulting cumulative distribution function becomes the fragility curve, from which damage state exceedance probabilities can be calculated. In the last step, the exceedance probabilities given by the cumulative distribution function are discretized to obtain discrete probabilities of being in each damage state. As a result, these curves capture the uncertainty of being in a specific damage state or another as they provide the complete probability distribution of having different damage states. These curves are often used for earthquake and tsunami damage calculation and can be used for other hazards as well. The result is a set of probabilities of attaining a certain level of damage or no damage. The sum of these probabilities is 100 percent. Figure 6.18 depicts an example of a fragility curve for earthquakes.

Figure 6.18. Example of Fragility Curves (for earthquake - Hazus 4.2 2018).



Additionally, and to consider social vulnerability (in terms of casualties), Hazus also provides casualty functions that estimate the number of casualties as a function of damage state of the asset and the construction type. It identifies four different levels of casualties:

Level 1: Injury, no hospitalization required

Level 2: Injury, hospitalization required

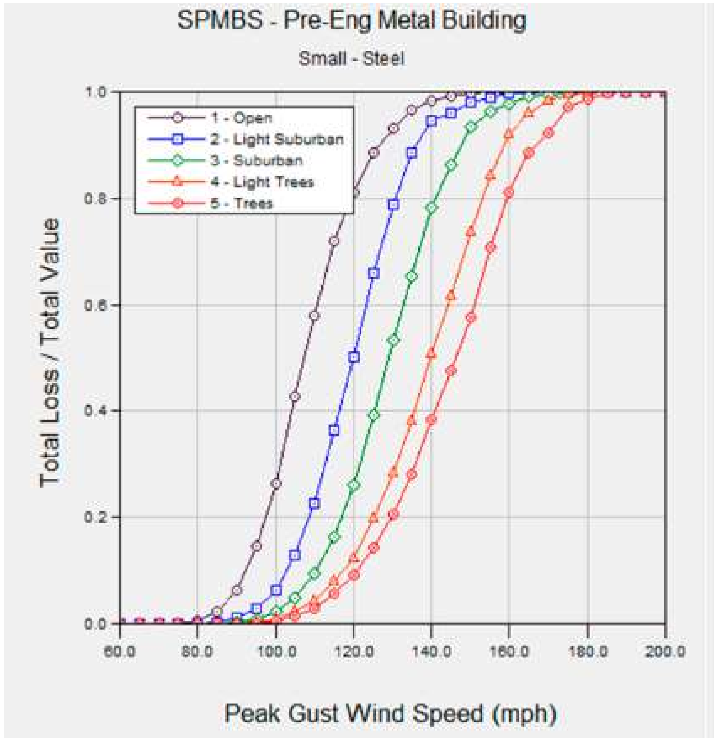
Level 3: Life-threatening injury, hospitalization required

Level 4: Death

For all building types, a slightly damaged structure would cause 0.5 level 1 casualties per 1,000 people. Appendix F shows the tables for moderately, severely and completely damaged structures. All the values shown in these tables represent casualties per 1,000 people.

c) CAPRA is a platform that was developed (with the technical and financial support of the IDB, the World Bank, and the United Nations International Strategy for Disaster Reduction) as an open-source and open-access tool specifically for the assessment of probabilistic multi-hazard risk (Cardona et al., 2011). CAPRA's vulnerability module consists of vulnerability curves, which represent the response of a structure to a wide range of solicitations in terms of a damage ratio usually expressed as a percentage of the value of the structure. Vulnerability curves are inherently probabilistic since they are built by treating the damage or loss as a random variable following a Beta distribution from which its main statistical moments (expected value and standard deviation) create the functions (ERN-AL, n.d. e). The process to construct these curves consists of, first, obtaining the response of the structure, second, applying the probabilistic treatment of the damage, and third, computing the expected value and standard deviation of the damage. For the first step, a structural analysis is conducted using any of the abovementioned methods. In the second step, the damage is treated as a random variable following a Beta distribution. In the last step, the probability distribution is used to calculate the statistical moments, expected value and standard deviation, both of which become the vulnerability curve. As a result, these curves capture the uncertainty of having a certain level of damage as they provide the complete probability distribution. These curves are often used for earthquake and flooding damage calculation and can be used for other hazards as well. An example of a vulnerability function for hurricane wind is shown in Figure 6.19.

Figure 6.19. Example of a Vulnerability Curve for Hurricane Wind



For a deterministic treatment of the vulnerability component (to be used in a deterministic risk assessment and using a corresponding deterministic hazard assessment and the detailed individual asset exposure approach), the last two approaches may be used indirectly by performing the abovementioned structural analyses, taking both capacity and demand parameters as a given and determining the corresponding response or damages directly and taking it as certain. In other words, it consists of removing the probabilistic dimension of the approaches, which considers a range of possibilities and probabilities of having varying damage states or values, and taking mean damage values or a specific damage state as given.

3. Create Loss of Use Functions:

Indirect losses include loss of functionality that leads to business interruption. This involves first determining the amount of time, on average, that assets remain inoperable. This time frame is required to calculate the business interruption losses and should be determined as a function of the intensity of the hazard of concern. A loss of use function enables the amount of time that a project component will be unusable after a disaster to be identified. Hazus' fragility functions and CAPRA's vulnerability curves also provide methods to create loss of use functions and functions for losses in contents.

For a detailed vulnerability assessment, business information specific to the project can be determined through surveys and interviews with project stakeholders. Information on the typical duration of business interruption following an event and on the costs of disruption, income, and wages, among others, needs to be collected.

The corresponding economic losses due to business interruption have been identified as: (i) relocation expenses and rental income losses; (ii) capital-related, output, and employment loss; and (iii) wage loss. The total business interruption is the combination of all three types of losses. For all hazards, use the following equations to calculate the business interruption losses.

$$Relocation\ loss = Disruption\ Costs + Recovery\ Time \cdot (Rental\ Costs)$$

where recovery time, disruption costs, and rental costs are surveyed or approximated for the specific project (see Appendix F for details on how to survey and collect these data).

$$Rental\ Income\ loss = Recovery\ Time \cdot (Rental\ Costs)$$

where recovery time and rental costs are surveyed or approximated for the specific project (see Appendix F for details on how to survey and collect these data).

$$Capital\ loss = (1 - Income\ Recapture\ Factor) \cdot Income\ Per\ Day \cdot Recovery\ Time$$

where recovery time, income per day, and the income recapture factor are surveyed or approximated for the specific project (see Appendix F for details on how to survey and collect these data).

$$Wage\ loss = (1 - Wage\ Recapture\ Factor) \cdot Wage\ Per\ Day \cdot Recovery\ Time$$

where recovery time, wage per day, and wage recapture factor are surveyed or approximated for the specific project (see Appendix F for details on how to survey and collect these data).

Finally, total losses for the project are calculated using the following equation:

$$Total\ loss = \underbrace{Structural\ Loss + Content\ Loss + Inventory\ Loss}_{Direct\ Losses} + \underbrace{Business\ Interruption\ Loss}_{Indirect\ Losses}$$

Topological Assessment

This approach requires less detailed information on the project component(s) to be evaluated than the detailed structural modeling approach. Vulnerability characteristics are collected for the elements as a whole, and assumptions may be made if detailed information is unavailable. Existing vulnerability and/or fragility functions are then used to generate loss estimates. This approach should also be used to assess communities in or near the project area. This approach consists of three activities: (i) identify specific characteristics that determine vulnerability, (ii) identify specific vulnerability functions, and (iii) identify specific loss of use functions.

1) Identify specific characteristics that determine vulnerability:

For proposed buildings and infrastructure, characteristics may be collected from design documents and through calls with the designer and developer. For existing buildings and infrastructure, an engineer may be needed to inspect the site and complete a survey. The specific characteristics required are provided by hazard type in the next section (see Hazard Specific Vulnerability Considerations below). These include how the buildings were constructed, the materials used, and key aspects which make them more or less vulnerable to the specific hazard.

2) Identify and use vulnerability and/or fragility functions:

Fragility and vulnerability functions such as those developed under the detailed structural modeling approach above and exist in the literature cover a large range of hazards and types of structures (e.g., flooding, ground shaking, wind speeds, flame length, tsunami flux, and landslide volumes, among others). The more detail a risk assessor identifies, the more accurate the vulnerability function they can select. Table 6.6 provides available vulnerability function resources. Some are created using statistics from many events, while others are created using a physical model approach that uses loads on structures and predicted failures of structural components, and still others are developed using expert input. Using the resources below and the characteristics identified in the previous activity, damage functions applicable to the project should be identified.

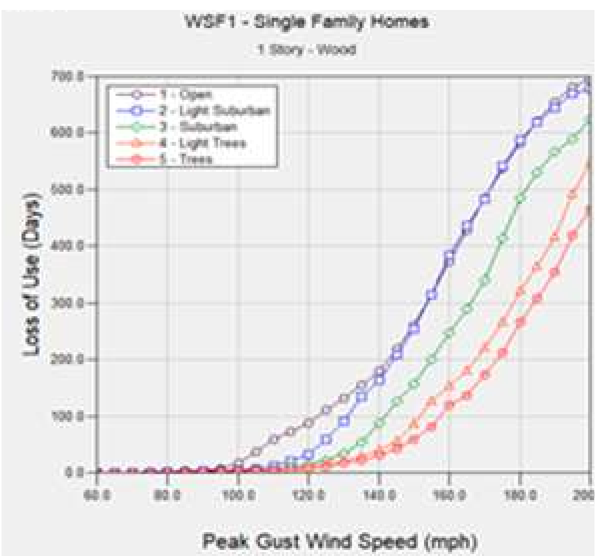
Table 6.6. Resources for Vulnerability and Fragility Functions

Hazard	Source	Link
Flood	U.S. Army Corps of Engineers	http://www.dtic.mil/dtic/tr/fulltext/u2/a255462.pdf
	U.S. Federal Insurance Administration	https://www.fema.gov/media-library/assets/documents/24609
	U.S. FEMA (Hazus)	https://www.fema.gov/media-library/assets/documents/24609
	UK's Multi-Coloured Manual	https://www.mcm-online.co.uk/
	European Commission JRC Model	http://publications.jrc.ec.europa.eu/repository/handle/JRC105688
	Flemish Model	n/a
	Damage Scanner	n/a
	FLEMO	http://onlinelibrary.wiley.com/doi/10.1111/risa.12650/full
	CAPRA	https://www.ecapra.org/topics/ern-flood
Wind	U.S. FEMA (Hazus)	https://www.fema.gov/media-library/assets/documents/24609
	CAPRA	https://www.ecapra.org/topics/ern-hurricane
	Florida International University	https://www4.cis.fiu.edu/hurricaneloss/html/model001.html#10
Earth-quake	ATC-63	https://www.atcouncil.org/atc-63
	FEMA/NIBS/RMS (Hazus)	https://www.fema.gov/media-library/assets/documents/24609
	FEMA 757	https://www.fema.gov/media-library/assets/documents/757
	Vision2000	http://www.seaoc.org/page/2015SSDMV2
	CAPRA	https://www.ecapra.org/topics/earthquake
	GEM	https://www.globalquakemodel.org/
Wildfire	U.S. Forest Service	https://www.fs.fed.us/wwetac/old/projects/vaillant.html
Landslide	Geological Society of London	http://qjegh.lyellcollection.org/user/logout?current=node/13382
	CAPRA	https://ecapra.org/topics/vulnerability
Tsunami	U.S. FEMA (Hazus)	https://www.fema.gov/media-library/assets/documents/24609
	CAPRA	https://ecapra.org/topics/vulnerability
Volcanic	CAPRA	https://ecapra.org/topics/vulnerability

3) Identify Loss of Use Functions:

A loss of use function enables the length of time a project component will be unusable after a disaster to be determined. This loss of use value is imperative for calculating business interruption losses. For a topological vulnerability assessment, general and typified business information can be determined from days of loss-of-use functions that exist in literature and which can be used. Figure 6.20 shows an example of a loss-of-use function for hurricane wind. Loss-of-use functions can be found in the Hazus links above. Using the resources above, specific loss of use functions applicable to the project components should be identified. If loss-of--use functions are not available for the hazard(s) of interest, assumptions can be made based on the damage the structure has suffered.

Figure 6.20. Example of a Loss of Use Function



For most hazards, Table 6.7 (Hazus 4.2, 2018) can be used to determine the loss of use value, in days (specific loss-of-use functions are given for flood and hurricane wind in the following sections). The loss of use is a function of the building occupancy and the damage state. For example, a retail trade structure which has been moderately damaged will be unusable for 90 days. If these values are not realistic for the asset's community, they may be updated for more accurate results.

Table 6.7. Loss of Use Table for Other Hazards

Description	Number of days			
	None	Slight	Moderate	Extensive
Agriculture	0	2	20	60
Retail trade	0	10	90	270
Parking	0	5	60	180
Wholesale trade	0	10	90	270
Personal and repair services	0	10	90	270
Professional/technical services	0	20	90	360
Banks	0	20	90	180
Hospital	0	20	135	540
Medical office/clinic	0	20	135	270
Entertainment and recreation	0	20	90	180
Theaters	0	20	90	180
Grade schools	0	10	90	360
Colleges/universities	0	10	120	480
General services	0	10	90	360
Emergency response	0	10	60	270
Heavy	0	10	90	240
Light	0	10	90	240
Food/drugs/chemicals	0	10	90	240
Metals/minerals processing	0	10	90	240
High technology	0	20	135	360
Construction	0	10	60	160
Churches and other non-profit org.	0	5	120	480
Single-family dwelling	0	5	120	360
Manuf. housing	0	5	20	120
Duplex	0	10	120	480
Triplex / quads	0	10	120	480
Multi-dwellings (5 to 9 units)	0	10	120	480
Multi-dwellings (10 to 19 units)	0	10	120	480
Multi-dwellings (20 to 49 units)	0	10	120	480
Multi-dwellings (50+ units)	0	10	120	480
Temporary lodging	0	10	90	360
Institutional dormitory	0	10	90	360
Nursing home	0	10	120	480

The corresponding subsequent calculation of economic losses due to business interruption is made in the same way as for the detailed assessment above, but where recovery time is determined from existing loss-of-use functions and the costs are estimated using available secondary data.

If the exposure was constructed using spatial aggregation instead of following the procedure described above for individual structures, an area-weighted analysis must be conducted for each polygon shape. The percentage of each hazard magnitude will need to be calculated for a portion of the asset polygon. The average loss of use (days) should be calculated using all the hazard and table values.

***Historical Timeline Analysis**

This type of analysis is a simplified risk assessment method used specifically for the agriculture sector. This method is treated as a special case in this Methodology, since more detailed disaster risk models for the agricultural sector are still very new and under development. Hence, the other more standardized approaches detailed in this Methodology for the hazard, exposure, and vulnerability components do not necessarily apply to this sector.

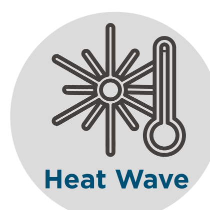
This method was developed by the World Bank (2016) in its Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners. This method does not aim to develop hazard or vulnerability models in depth; instead, it estimates agricultural production losses due to natural hazards using historical loss data. Hence, within this risk approach, the vulnerability is treated implicitly through the assumed correlation and causation between an observed decrease in productivity and the concurrent occurrence of an event. No explicit vulnerability activities need be conducted for this risk assessment. See the [simplified agricultural risk assessment] in the Quantification of the Disaster and Climate Change risk section below for details on the risk calculation.

Hazard-specific vulnerability considerations:

People are in general vulnerable to all hazards. Thus, employee and community demographic information needs to be collected, regardless of the hazard, and their vulnerability assessed. Because different hazards have different physical expressions, the physical characteristics that determine the vulnerability of a structure will depend on the hazard.

To show how each of the approaches mentioned in Table 6.5 is used, the hazards have been grouped together based on a common vulnerability approach. Additionally, the length of time that an asset will be inoperable must be determined. This time frame is required to calculate the business interruption losses. There are different ways to make this calculation depending on which hazard is of concern. For both the vulnerability and the functionality assessment, the hazards have been grouped differently based on the approach. The typical vulnerability considerations and methods per hazard are discussed below.

6.1.4.4.2 Drought and heatwave



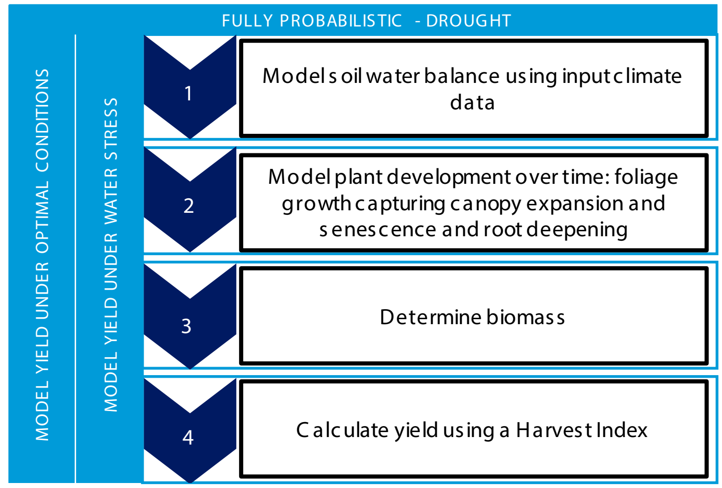
Usually infrastructure in general is considered not to be vulnerable to these hazards, as changes in temperature or water scarcity do not affect them physically.

For heatwave, an exception could be made for roads, where heatwaves could impact pavement durability, or for other infrastructure that is sensitive to extreme temperatures. Furthermore, for populations, having or not having access to active or passive cooling is a key social vulnerability factor. This may require sufficient electricity or access to community-level cooling centers; access, funds for running air conditioners, a reliable electricity network, and availability of basements are elements of vulnerability.

The agricultural sector is vulnerable to drought, where plantations/crops are the main assets to be considered. The main characteristics that determine vulnerability for crops are the type of crop, its water demand, and its growth cycle (phenological stages).

Detailed structural modeling (for individual assets): A detailed method to be used in an agricultural drought risk assessment is summarized here since, as it is the only sector that is obviously affected by drought. The method corresponds to the approach proposed by Bernal et al. (2017) of a fully probabilistic agricultural drought risk framework that was introduced above in the drought hazard section and which includes a detailed crop vulnerability module. This module follows the Food and Agricultural Organization's (FAO) method described in the Irrigation and Drainage Paper No. 66: Crop Yield Response to Water (Steduto et al., 2012), which defines vulnerability as the difference between a crop's optimum yield and the resulting yield under water stress. A crop's yield response to water availability is evaluated by modeling (using the AquaCrop software, see Raes et al., 2011) crop development, soils, and agricultural management to calculate crop biomass and, ultimately, yield. Figure 6.21 summarizes the proposed agricultural vulnerability procedure (see Steduto et al.,2012 and Bernal et al., 2017 for details).

Figure 6.21. Main Steps in an Agricultural Vulnerability Assessment



The following steps, summarized in Figure 6.21, are conducted for both an optimal scenario in which there is no water stress (or any other limitations) and a scenario under water stress that incorporates the drought conditions.

1. Using the climate data as input, the soil water balance is modeled to determine a water stress coefficient which affects plant growth.

2. The plant development is modeled over time for all phenological stages (vegetative, flowering, yield formation, and ripening). A reference canopy cover function is obtained using a canopy growth coefficient under optimal conditions, and then the actual canopy cover function is determined by multiplying the canopy growth coefficient by the water stress coefficient.

3. Plant transpiration is calculated from the canopy cover function (also including the water stress coefficient), and then the amount of biomass is calculated as a function of the plant's transpiration and a water productivity parameter that indicates the amount of biomass produced per unit amount of transpiration.

4. Finally, yield is calculated as the proportion of biomass that becomes harvestable. The biomass is multiplied by a harvest index. Yields under optimal conditions and under drought conditions are determined and compared to determine the yield loss.

This vulnerability approach should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic agricultural risk assessment.

Topological assessment (for multiple assets): The agricultural vulnerability method described above for the detailed structural modeling can also be used in a topological vulnerability assessment for multiple assets. In this case, the crops may be grouped and general assumptions about them can be made. This vulnerability approach should be used with a probabilistic hazard assessment approach and with the proxy – aggregated exposure approach to obtain a probabilistic agricultural risk assessment.

***Historical Timeline Analysis:** the last option, again only for the agriculture sector, is the simple method used in the Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners developed by the World Bank (2016). Within this risk approach, the vulnerability component is treated implicitly through the assumed correlation and causation between an observed decrease in productivity and the concurrent occurrence of an event. No explicit vulnerability activities need be conducted for this risk assessment. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section below for details on the risk calculation.

To create or assign loss-of-use functions, the general values given in Table 6.6 should be used according to approximate damage states for various sectors.

6.1.4.4.3 Earthquake

Unlike for drought and heatwave, most infrastructure is usually considered vulnerable to seismic hazard, as ground shaking affects everything that is on the ground. What varies is the level of vulnerability, where certain types of structures are more or less vulnerable than others. For most structures (including buildings and bridges) the main structural characteristics that influence their vulnerability include the structural typology or structural system and their lateral force resisting system (e.g., moment-frames versus braced frames), structural period of vibration (this implicitly includes structure height), type of foundation, construction materials (e.g., reinforced concrete, steel or masonry), and overall condition. For infrastructure such as pipelines (e.g., water and sanitation networks), the material (e.g., concrete versus PVC) and type of joints (e.g., rigid versus flexible) are the main characteristics.

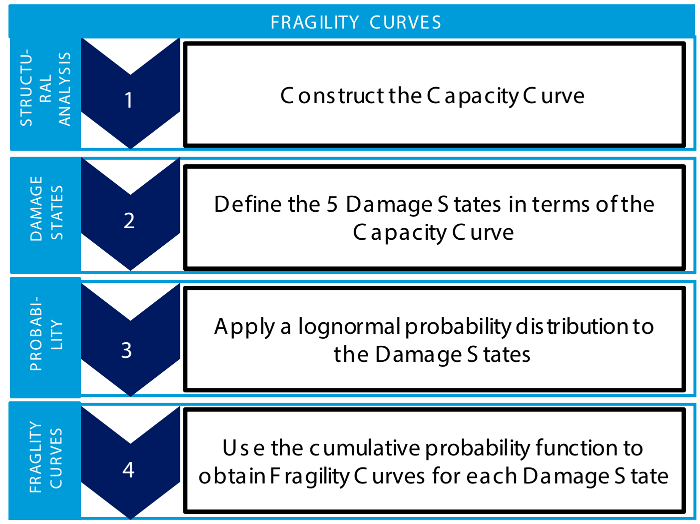
Detailed structural modeling (for individual assets): Structural engineering techniques should be used to model the response of a structure to seismic demands. There is a wide range of methods and techniques to do this, as this has always been deeply embedded in engineering practice. The vulnerability component of a risk assessment is the structural analysis in traditional engineering language.

The major groups of methods used to perform structural analysis include linear elastic static analysis (equivalent lateral force analysis), linear elastic dynamic analysis (modal response spectrum analysis), incremental non-linear static analysis (pushover analysis), non-linear dynamic analysis (single time history analysis) and incremental non-linear dynamic analysis (incremental time history analysis). These are described in ASCE/SEI 7-16 (ASCE, 2016), ASCE/SEI 7-10 (ASCE, 2010), Vamvatsikos and Cornell (2002), and FEMA-350 (FEMA, 2000). The performance of a structure is then evaluated through a set of indicators such as desired deformation patterns, maximum allowable drift, and ductility characteristics, among others. However, to integrate this into a risk assessment, these detailed structural indicators must be translated into a more global measure (in terms of a structure as a whole) that allows a broader and more understandable quantification of damage. To do this, three main approaches can be used: applying structural reliability theory, using the Hazus approach of generating fragility curves (FEMA, n.d.) and using the CAPRA approach of generating Vulnerability Curves (ERN-AL, n.d. e). Both Fragility Curves and Vulnerability Curves should be constructed as a function of spectral acceleration (Sa) or spectral displacement (Sd).

a. For the first approach, the structural reliability theory is applied to the detailed structural analyses to ultimately calculate probabilities of failure or collapse (see Franchin et al., 2012; Lazar and Dolsek, 2012; Todinov, 2008; Wayan, 2012).

b. For the second approach (fragility curves), Figure 6.22 summarizes the process of constructing these curves (see FEMA, n.d.a; Zuloaga, 2014).

Figure 6.22. Procedure to Construct Fragility Curves



1. A structural analysis method is selected (see available methods above) to model the behavior and response of the structure to seismic demands. This response is expressed via the capacity curve, which is a graphical representation of the capacity of the structure in terms of deformation with increasing ground motion (usually these curves depict roof displacement or spectral displacement versus spectral acceleration).

2. Critical parameters are obtained from the capacity curve, including the yielding and ultimate points. Then, damage states are established from these parameters. As a result, the five damage states (none, slight, moderate, severe, and collapsed) are represented by threshold spectral displacement values.

3. A lognormal probability distribution is assigned to the damage states for which the relevant statistical moments are determined (median and standard deviation) and the distribution parameters computed.

4. The cumulative probability function representing the probability of being in or exceeding a particular damage state

becomes the fragility function. Five fragility functions are obtained, one for each damage state. Discrete probabilities of exactly being in a particular damage state can then be computed from these curves and stored in what is called the damage probability matrix.

Fragility curves can be built for the structure, non-structural drift sensitive components (nonbearing walls/partitions, exterior wall panels, veneer, and finishes), and non-structural acceleration-sensitive components (cantilever elements and parapets, appendages and ornaments, racks and cabinets, piping systems, storage tanks, HVAC systems, elevators, and lighting fixtures).

The last consideration is an increase in complete damage due to ground deformation from liquefaction and landslide susceptibility. Assets exposed to these two earthquake-induced hazards should have their complete damage probability increased and other probabilities decreased proportionately. The probability increase follows the tables below.

Table 6.8. Liquefaction and Landslide Considerations

Amplification Factors | Liquefaction | **Landslide**

Table

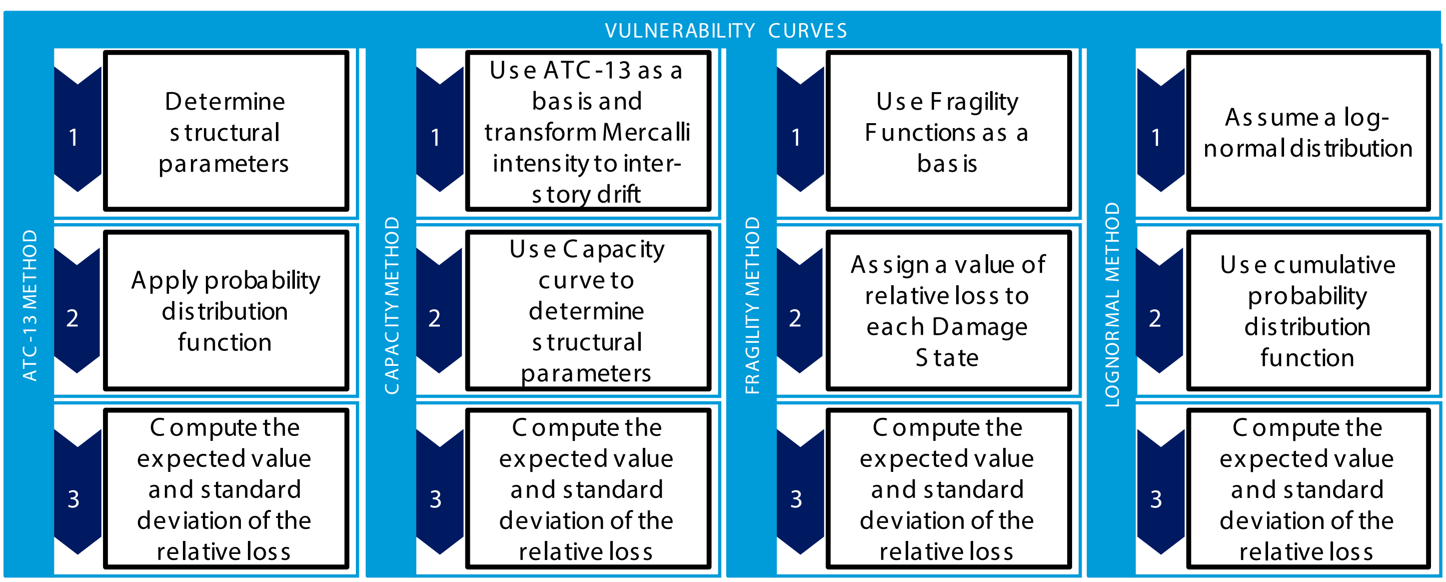
	Susceptibility	Class	Proportion
1	0	None - Dry	0.00
2	1	None - Wet	0.01
3	2	Very Low - Dry	0.02
4	3	Very low - Wet	0.03
5	4	Low - Dry	0.05
6	5	Low - wet	0.08
7	6	Moderate - Dry	0.10
8	7	Moderate - Wet	0.15
9	8	High - Dry	0.20
10	9	High - Wet	0.25
11	10	Very High	0.30

Source: Hazus 4.2 (2018).

Finally, the contents and business inventory damage is based on the structural damage state probability.

c. For the third approach (vulnerability curves), there are several methods to construct these curves, including at least the following: (i) ATC-13 method, (ii) capacity method, (iii) fragility method and (iv) log-normal method. Figure 6.23 summarizes the different processes of constructing these curves (see ERN-AL, n.d.e; Cardona et al., 2017a).

Figure 6.23. Procedure to Construct Vulnerability Curves



5. In the ATC-13 method, the ATC-13 Report (Earthquake Damage Evaluation Data for California) is used to determine the damage associated to seismic demands in terms of Mercalli intensity (see ATC, 1985).

6. In the capacity method, the ATC-13 is used as a base, but it is modified to use the capacity curve to determine structural parameters and transform from Mercalli intensity to inter story drift. As a result, the equation given by ATC-13 is modified by a list of parameters (see Miranda, 1999; Ordaz, 2000).

7. In the fragility method, fragility curves are used as a basis for which relative loss values are assigned to the different damage states. The expected value of the relative loss is then computed (see Barbat et al., 2013; Barbat et al., 1996; CIMNE et al., 2013; Irizarry et al., 2011; Mouroux and Le Brun, 2008; Ordaz, 2008; Zuloaga, 2014).

8. In the log-normal method, it is assumed that the expected value of the relative loss can be computed using the cumulative probability function of a log-normal distribution (see Cardona et al., 2017a).

For a probabilistic risk assessment (and using a corresponding probabilistic hazard assessment), any of the three approaches detailed above provides the required probabilistic treatment of the vulnerability component. This vulnerability approach should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment (and using a corresponding deterministic hazard assessment), mean damage values or damage states estimated after performing the structural analysis for a particular seismic demand may be assumed as certain (with no consideration of uncertainty). As a result, the behavior of the structure is taken directly from the structural analyses, which in turn are performed for a single (and assumed as certain) seismic solicitation and without considering uncertainty in the engineering problem or design. This vulnerability approach should be used with the deterministic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a deterministic risk assessment.

Topological assessment (for multiple assets): Existing fragility and/or vulnerability functions should be used. Using the abovementioned characteristics that determine seismic vulnerability (structural system, etc.), damage functions which are adequate for the existing different typologies of structures should be identified. Table 6.6 provides available vulnerability and fragility function resources. If the exposure database is spatially individualized (even though the assets are grouped by typologies, individual assets, such as building by building, are still identified and assigned a typology), then each individual structure must have an assigned curve. If the exposed assets were further aggregated spatially (e.g., into blocks, neighborhoods, or municipalities), instead of assigning curves to individual structures, the building types are grouped by square footage and vulnerability or fragility functions are assigned to the grouped units representing the average or most representative topology present within.

For a probabilistic risk assessment, the selected fragility and/or vulnerability curves must be used with their complete probabilistic representation (for vulnerability curves this means including the standard deviation function as well into the risk calculations). This vulnerability approach should be used with the probabilistic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment, mean damage values or damage states may be used from the vulnerability and/or fragility curves. This vulnerability approach should be used with the deterministic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a deterministic risk assessment.

To determine percentage loss values associated with different damage states and typology, Table 6.9 may be used. To determine building content losses and business inventory losses, Table 6.10, which has values depending on structural damage state, may be used. To create or assign loss-of-use functions the general values in Table 6.7 should be used according to approximate damage states for various sectors.

Table 6.9. Earthquake Structural and Non-Structural Losses Based on Damage State Probabilities and Occupancy Types

	Structural				Acceleration Sensitive				Drift Sensitive			
Description	**Slight**	**Moderate**	**Extensive**	**Complete**	**Slight**	**Moderate**	**Extensive**	**Complete**	**Slight**	**Moderate**	**Extensive**	**Complete**
Agriculture	0.8	4.6	23.1	46.2	0.8	4.6	13.8	46.1	0	0.8	3.8	7.7
Retail Trade	0.6	2.9	14.7	29.4	0.8	4.4	12.9	43.1	0.6	2.7	13.8	27.5
Parking	1.3	6.1	30.4	60.9	0.3	2.2	6.5	21.7	0.4	1.7	8.7	17.4
Wholesale Trade	0.6	3.2	16.2	32.4	0.8	4.2	12.4	41.1	0.6	2.6	13.2	26.5
Personal and Repair Services	0.3	1.6	8.1	16.2	1	5	15	50	0.7	3.4	16.9	33.8
Professional/Technical Services	0.4	1.9	9.6	19.2	0.9	4.8	14.4	47.9	0.7	3.3	16.4	32.9
Banks	0.3	1.4	6.9	13.8	1	5.2	15.5	51.7	0.7	3.4	17.2	34.5
Hospital	0.2	1.4	7	14	1	5.1	15.4	51.3	0.8	3.5	17.4	34.7
Medical Office/Clinic	0.3	1.4	7.2	14.4	1	5.2	15.3	51.2	0.7	3.4	17.2	34.4
Entertainment & Recreation	0.2	1	5	10	1.1	5.4	16.3	54.4	0.7	3.6	17.8	35.6
Theaters	0.3	1.2	6.1	12.2	1	5.3	15.8	52.7	0.7	3.5	17.6	35.1
Grade Schools	0.4	1.9	9.5	18.9	0.7	3.2	9.7	32.4	0.9	4.9	24.3	48.7
Colleges/Universities	0.2	1.1	5.5	11	0.6	2.9	8.7	29	1.2	6	30	60
General Services	0.3	1.8	9	17.9	1	4.9	14.8	49.3	0.7	3.3	16.4	32.8
Emergency Response	0.3	1.5	7.7	15.3	1	5.1	15.1	50.5	0.7	3.4	17.1	34.2
Heavy	0.4	1.6	7.8	15.7	1.4	7.2	21.8	72.5	0.2	1.2	5.9	11.8
Light	0.4	1.6	7.8	15.7	1.4	7.2	21.8	72.5	0.2	1.2	5.9	11.8
Food/Drugs/Chemicals	0.4	1.6	7.8	15.7	1.4	7.2	21.8	72.5	0.2	1.2	5.9	11.8
Metals/Minerals Processing	0.4	1.6	7.8	15.7	1.4	7.2	21.8	72.5	0.2	1.2	5.9	11.8
High Technology	0.4	1.6	7.8	15.7	1.4	7.2	21.8	72.5	0.2	1.2	5.9	11.8
Construction	0.4	1.6	7.8	15.7	1.4	7.2	21.8	72.5	0.2	1.2	5.9	11.8
Churches and Other Non-profit Or	0.3	2	9.9	19.8	0.9	4.7	14.3	47.6	0.8	3.3	16.3	32.6
Single Family Dwelling	0.5	2.3	11.7	23.4	0.5	2.7	8	26.6	1	5	25	50
Manuf. Housing	0.4	2.4	7.3	24.4	0.8	3.8	11.3	37.8	0.8	3.8	18.9	37.8
Duplex	0.3	1.4	6.9	13.8	0.8	4.3	13.1	43.7	0.9	4.3	21.3	42.5
Triplex / Quads	0.3	1.4	6.9	13.8	0.8	4.3	13.1	43.7	0.9	4.3	21.3	42.5
Multi-dwellings (5 to 9 units)	0.3	1.4	6.9	13.8	0.8	4.3	13.1	43.7	0.9	4.3	21.3	42.5
Multi-dwellings (10 to 19 units)	0.3	1.4	6.9	13.8	0.8	4.3	13.1	43.7	0.9	4.3	21.3	42.5
Multi-dwellings (20 to 49 units)	0.3	1.4	6.9	13.8	0.8	4.3	13.1	43.7	0.9	4.3	21.3	42.5
Multi-dwellings (50+ units)	0.3	1.4	6.9	13.8	0.8	4.3	13.1	43.7	0.9	4.3	21.3	42.5
Temporary Lodging	0.2	1.4	6.8	13.6	0.9	4.3	13	43.2	0.9	4.3	21.6	43.2
Institutional Dormitory	0.4	1.9	9.4	18.8	0.8	4.1	12.4	41.2	0.8	4	20	40
Nursing Home	0.4	1.8	9.2	18.4	0.8	4.1	12.2	40.8	0.8	4.1	20.4	40.8

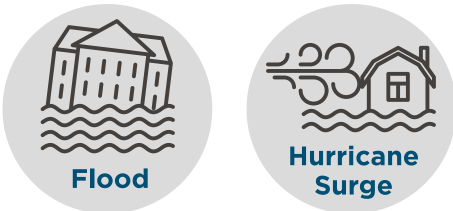
Source: Hazus 4.2 (2018).

Table 6.10. Earthquake Content and Business Inventory Losses Based on Damage State Probabilities and Occupancy Types

	Content Loss (%)				Inventory Loss (%)			
Occupancy	**Slight**	**Moderate**	**Extensive**	**Complete**	**Slight**	**Moderate**	**Extensive**	**Complete**
Agriculture	1	5	25	50	1	5	25	50
Retail Trade	1	5	25	50	1	5	25	50
Parking	1	5	25	50				
Wholesale Trade	1	5	25	50	1	5	25	50
Personal and Repair Services	1	5	25	50				
Professional/Technical Services	1	5	25	50				
Banks	1	5	25	50				
Hospital	1	5	25	50				
Medical Office/Clinic	1	5	25	50				
Entertainment & Recreation	1	5	25	50				
Theaters	1	5	25	50				
Grade Schools	1	5	25	50				
Colleges/Universities	1	5	25	50				
General Services	1	5	25	50				
Emergency Response	1	5	25	50				
Heavy	1	5	25	50	1	5	25	50
Light	1	5	25	50	1	5	25	50
Food/Drugs/Chemicals	1	5	25	50	1	5	25	50
Metals/Minerals Processing	1	5	25	50	1	5	25	50
High Technology	1	5	25	50	1	5	25	50
Construction	1	5	25	50	1	5	25	50
Churches and Other Non-profit Org.	1	5	25	50				
Single Family Dwelling	1	5	25	50				
Manuf. Housing	1	5	25	50				
Duplex	1	5	25	50				
Triplex / Quads	1	5	25	50				
Multi-dwellings (5 to 9 units)	1	5	25	50				
Multi-dwellings (10 to 19 units)	1	5	25	50				
Multi-dwellings (20 to 49 units)	1	5	25	50				
Multi-dwellings (50+ units)	1	5	25	50				
Temporary Lodging	1	5	25	50				
Institutional Dormitory	1	5	25	50				
Nursing Home	1	5	25	50				

Source: Hazus 4.2 (2018).

6.1.4.4.4 Flooding (all types except tsunami)



Most structures are vulnerable to flooding, with certain types of structures being more or less vulnerable than others. As distinct from damage from earthquakes, a building is unlikely to suffer structural damage due to flooding (unless the flood carries high velocities and/or debris that can cause structural impact); rather, only non-structural components, finishes, and contents suffer damages. For buildings, the main characteristics that influence their vulnerability include the material of the walls and floors, type of foundation, the first-floor elevation above ground, and the number of stories. The presence of critical assets in first floors is also a key characteristic this is important for critical facilities such as hospitals. For bridges, a flood may cause structural damage to the foundation, piles, or abutments. Hence, the structural system (e.g., the number of spans and presence of piers) and freeboard height are characteristics that indicate vulnerability. Similarly, for roads, flooding may structurally damage the road base structure, eroding or washing away embankments. Water and sanitation infrastructure are generally not too vulnerable, but pipes that are designed to work unpressurized might suffer damages if they become pressurized.

Detailed structural modeling (for individual assets): In general, the response of infrastructure to flooding must be analyzed using engineering techniques specific to the type of infrastructure. Structural reliability theory may be applied to perform these analyses, especially for bridges, where structural damage is a concern. Vulnerability curves for the specific infrastructure under analysis may be created from this using empirical or analytical data to establish the levels of damage and relative loss (losses relative to the cost of replacing the structure) that correspond to increasing levels of flooding height. In the case of torrential flooding, the velocity of the flow may also be relevant; thus, the vulnerability curves created should also reflect relative damage in response to flow velocity. Both the Hazus and CAPRA methods use vulnerability curves, although Hazus refers to them as depth-damage functions (FEMA, n.d. b; ERN-AL, n.d.e).

For a probabilistic risk assessment, the vulnerability assessment has to be done probabilistically as well, using structural reliability of building vulnerability curves that consider this. This vulnerability approach should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment (and using a corresponding deterministic hazard assessment), mean damage values or damage states estimated after performing the structural analysis for a particular flooding demand may be assumed as certain (with no consideration of uncertainty). As a result, the behavior of a structure is taken directly from the analyses which in turn are performed for a single (and assumed as certain) flooding solicitation and without considering uncertainty in the engineering problem or design. This vulnerability approach should be used with the deterministic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a deterministic risk assessment.

Topological assessment (for multiple assets): Existing vulnerability functions (also called depth-damage functions) should be used. Using the abovementioned characteristics that determine flooding vulnerability, damage functions which are adequate for the existing different typologies of structures should be identified. Table 6.6 provides resources for available vulnerability functions. Both the Hazus and the CAPRA platforms use vulnerability functions and provide resources, including loss-of-use functions (ERN-AL, n.d.e; FEMA, n.d.b), as well as the European Union through the European Commission's Joint Research Center (Huizinga et al., 2017). If the exposure database is spatially individualized (even though the assets are grouped by typologies, individual assets, for example, building by building, are still identified and assigned a typology), then each individual structure must have an assigned curve. If the exposed assets were further aggregated spatially (e.g., into blocks, neighborhoods, or municipalities), instead of assigning curves to individual structures, the building types are grouped by square footage, and vulnerability functions are assigned to the grouped units representing the average or most representative topology present within.

For a probabilistic risk assessment, the selected vulnerability curves must be used with their complete probabilistic representation (for vulnerability curves this means including the standard deviation function as well into the risk calculations). This vulnerability approach should be used with the probabilistic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment, mean damage values or damage states may be used from the vulnerability curves. This vulnerability approach should be used with the deterministic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a deterministic risk assessment.

***Historical Timeline Analysis:** the last option, which applies only to the agriculture sector, is the simple method used in the Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners developed by the World Bank (2016). Within this risk approach, the vulnerability component is treated implicitly through the assumed correlation and causation between an observed decrease in productivity and the concurrent occurrence of an event. No explicit vulnerability activities need be conducted for this risk assessment. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section below for details on the risk calculation.

For flood, the loss-of-use functions are based on water depth. Table 6.11 shows an example of a loss-of-use function. If the flood depth value is between 0 and 4 feet, the loss of use is 360 days.

Table 6.11. Flood Loss of Use Table

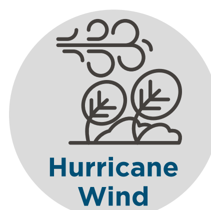
Occupancy: RES1

Time

	SpecificOccupancy	MinimumDepth	MaximumDepth	MaximumDaysForRestoration
1	RES1	-4	0	180
2	RES1	0	4	360
3	RES1	4	8	450
4	RES1	8	24	720

Source: Hazus 4.2 (2018).

6.1.4.5 Hurricane wind



Wind is a horizontal load that is treated like earthquakes in the design of structures, especially high-rise structures. Hence, important characteristics for buildings and bridges include the structural typology or structural system and its lateral force-resisting system (e.g., moment frames versus braced frames), structural period of vibration (implicitly including structure height), and roof type. Non-structural elements tend to suffer more than structural elements; thus, the anchoring elements for non-structural elements, shuttering, and hurricane straps are also important characteristics. Underground infrastructure such as pipeline networks or infrastructure that is low on the ground such as roads are not vulnerable to this hazard.

The application of the two vulnerability assessment methods (detailed structural modeling and topological assessment) is described below.

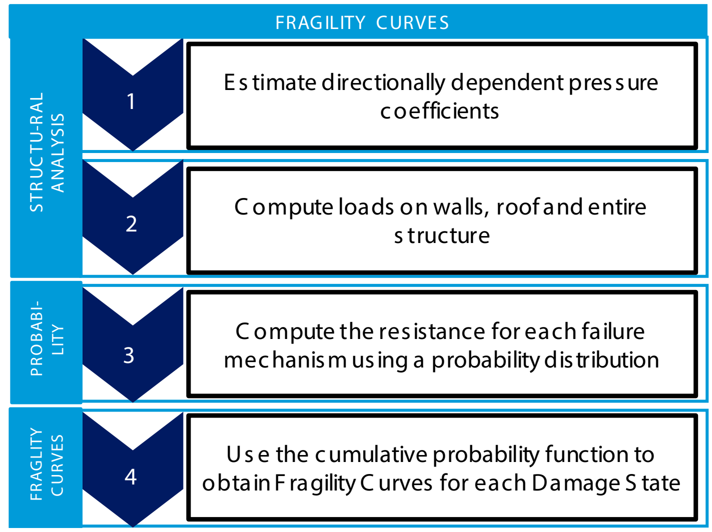
Detailed structural modeling (for individual assets): Structural engineering techniques should be used to model a structure's response to wind demands. There is a wide range of methods and techniques to do this, as this has always been deeply embedded in engineering practice. In this context, the vulnerability component of a risk assessment corresponds to the structural analysis in traditional engineering language.

Similar to the seismic vulnerability discussed above, to integrate this into a risk assessment, the structural analysis needs to be translated into a measure of damage. To do this, the same three main approaches can be used: applying structural reliability theory, using the Hazus approach of generating fragility curves (FEMA, n.d. c), and using the CAPRA approach of generating vulnerability curves (ERN-AL, n.d. e). Both fragility curves and vulnerability curves should be constructed as a function of peak gust wind speed.

a. For the first approach, the structural reliability theory is applied to the detailed structural analyses to ultimately calculate probabilities of failure or collapse (see Franchin et al., 2012; Lazar and Dolsek, 2012; Todinov, 2008; Wayan, 2012).

b. For the second approach (fragility curves), Figure 6.24 summarizes the process of constructing these curves (see FEMA, n.d. c).

Figure 6.24. Procedure to Construct Fragility Curves



1. A structural analysis method is selected to model the behavior and response of the structure to wind demands. This response is expressed via pressure coefficients, which depend on the load directionality. These coefficients are estimated for all building components and cladding.

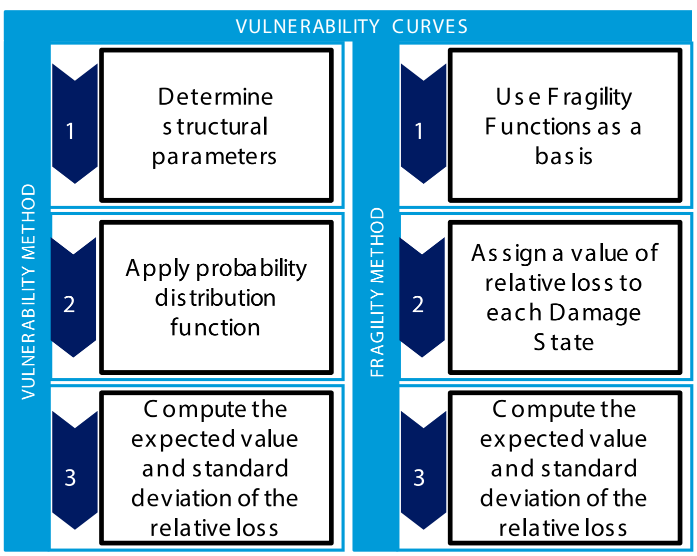
2. Then, the loads on walls, roof, and the entire building are computed to evaluate wall failures, roof-wall connection failures, and foundation failures.

3. Individual failure modes or mechanisms are evaluated, and the resistance of the structure is determined. A probability distribution (usually the log-normal distribution is used, although Weibull, normal, or other distributions may be applied as well) is assigned to the damage states for which the relevant statistical moments are determined (median and standard deviation) and the distribution parameters are computed.

4. The cumulative probability function representing the probability of being in or exceeding a particular damage state for a given peak gust wind speed becomes the fragility function. One fragility function is obtained for each damage state. Discrete probabilities of exactly being in a particular damage state can then be computed from these curves and stored in what is called the damage probability matrix.

c. For the third approach, vulnerability curves can also be built. Figure 6.25 summarizes the process of constructing these curves. There are two possible methods. The first corresponds to directly building vulnerability curves from structural analyses (see ERN-AL, n.d.e), and the second corresponds to transforming fragility curves to vulnerability curves (see Cardona et al., 2015).

Figure 6.25. Procedure to Construct Vulnerability Curves



In the vulnerability method, it is assumed that the relative loss follows a Beta distribution from which the expected value and standard deviation are determined and represent the vulnerability curve, which is a function of peak gust wind speed (see ERN-AL, n.d.e; Cardona et al., 2013).

In the fragility method, fragility curves are used as a basis to which relative loss values are assigned to the different damage states, and the expected value of the relative loss is then computed (see Cardona et al., 2015; CIMNE et al., 2013).

For a probabilistic risk assessment (and using a corresponding probabilistic hazard assessment), any of the three approaches detailed above provide the required probabilistic treatment of the vulnerability component. This vulnerability approach should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment (and using a corresponding deterministic hazard assessment), mean damage values or damage states estimated after performing the structural analysis for a particular wind demand may be assumed as certain (with no consideration of uncertainty). As a result, the behavior of a structure is taken directly from the structural analyses which in turn are performed for a single (and assumed as certain) wind solicitation and without considering uncertainty in the engineering problem or design. This vulnerability approach should be used with the deterministic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a deterministic risk assessment.

Topological assessment (for multiple assets): Existing fragility and/or vulnerability functions should be used. Using the abovementioned characteristics that determine hurricane wind vulnerability, damage functions which are adequate for the existing different typologies of structures should be identified. Table 6.6 provides available vulnerability and fragility function resources. If the exposure database is spatially individualized (even though the assets are grouped by typologies, individual assets, for example, building by building, are still identified and assigned a typology), then each individual structure must have an assigned curve. If the exposed assets were further aggregated spatially (e.g., into blocks, neighborhoods, or municipalities), rather than assigning curves to individual structures, the building types are grouped by square footage, and vulnerability or fragility functions are assigned to the grouped units representing the average or most representative topology present within.

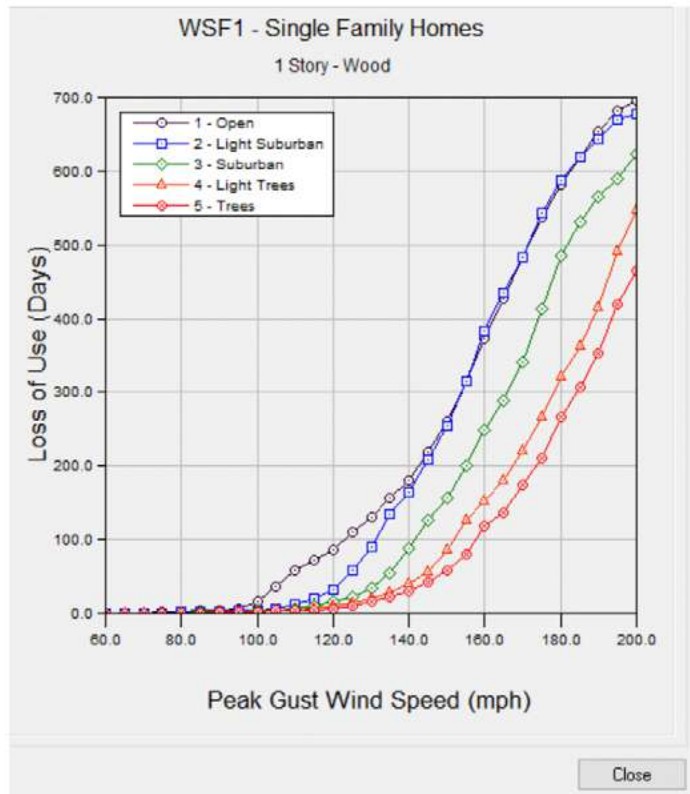
For a probabilistic risk assessment, the selected fragility and/or vulnerability curves must be used with their complete probabilistic representation (for vulnerability curves this means including the standard deviation function as well into the risk calculations). This vulnerability approach should be used with the probabilistic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment, mean damage values or damage states may be used from the vulnerability and/or fragility curves. This vulnerability approach should be used with the deterministic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a deterministic risk assessment.

***Historical Timeline Analysis:** the last option, which applies only to the agriculture sector, is the simple method used in the Agricultural Sector Risk Assessment: Methodological Guidance for Practitioners developed by the World Bank (2016). Within this risk approach, the vulnerability component is treated implicitly through the assumed correlation and causation between an observed decrease in productivity and the concurrent occurrence of an event. No explicit vulnerability activities need be conducted for this risk assessment. See the simplified agricultural risk assessment in the Quantification of the Disaster and Climate Change risk section below for details on the risk calculation.

For hurricane wind, the loss-of-use functions are based on wind speed and terrain values. Figure 6.26 depicts an example of a loss-of-use function.

Figure 6.26. Hurricane Loss of Use Function



Source: Hazus 4.2 (2018).

6.1.4.6 Landslides

For buildings, the main characteristics to consider in assessing landslide hazard are construction materials, the structural system, the type of foundation, and the presence of slope stabilization structures. For linear infrastructure such as roads, the presence and type of slope stabilization structures are also characteristics to be considered.

Detailed structural modeling (for individual assets): It is less common to construct or find damage functions for landslides. However, structural engineering techniques can be used to model the behavior of a structure under different landslide susceptibility. Hence, the number of approaches to model the vulnerability of a structure to landslides is more limited than for other hazards. The structural reliability approach and the CAPRA approach can be used to generate vulnerability curves (ERN-AL, n.d.e). Vulnerability curves should be constructed as a function of the inverse of the factor of safety.

a. For the first approach, structural reliability theory is applied to the detailed structural analyses to ultimately calculate probabilities of failure or collapse (see Franchin et al., 2012; Lazar and Dolsek, 2012; Todinov, 2008; Wayan, 2012).

b. For the second approach, vulnerability curves can also be built. It is assumed that the relative loss follows a Beta distribution from which the expected value and standard deviation are determined and represent the vulnerability curve, which is a function of the inverse of the factor of safety (see ERN-AL, n.d.e).

For a probabilistic risk assessment (and using a corresponding probabilistic hazard assessment), either of the two approaches detailed above provides the required probabilistic treatment of the vulnerability component. This vulnerability approach is not very common, but if it is used it should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment (and using a corresponding deterministic hazard assessment), mean damage values or damage states estimated after performing the structural analysis for a particular landslide susceptibility scenario may be assumed as certain (with no consideration of uncertainty). As a result, the behavior of the structure is taken directly from the structural analyses which in turn are performed for a single (and assumed as certain) landslide susceptibility situation and without considering uncertainty in the engineering problem or design. This vulnerability approach should be used with the deterministic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a deterministic risk assessment.

Topological assessment (for multiple assets): Although rare, existing vulnerability functions should be used. Using the abovementioned characteristics that determine vulnerability to landslides, damage functions which are adequate for the existing different typologies of structures should be identified. Table 6.6 provides available vulnerability function resources. If the exposure database is spatially individualized (even though the assets are grouped by typologies, individual assets, such as building by building, are still identified and assigned a typology), then each individual structure must have an assigned curve. If the exposed assets were further aggregated spatially (e.g., into blocks, neighborhoods, or municipalities), rather than assigning curves to individual structures, the building types are grouped by square footage, and vulnerability functions are assigned to the grouped units representing the average or most representative topology present within.

For a probabilistic risk assessment, the selected vulnerability curves must be used with their complete probabilistic representation (for vulnerability curves this means including the standard deviation function as well into the risk calculations). This vulnerability approach should be used with the probabilistic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment, mean damage values or damage states may be used from the vulnerability curves. This vulnerability approach should be used with the deterministic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a deterministic risk assessment.

To create or assign loss-of-use functions, the general values given by Table 6.7 should be used according to approximate damage states for various sectors.

6.1.4.4.7 Tsunami

The main characteristics of a structure that influence its vulnerability to tsunami inundation include the material of the walls and floors, the type of foundation, the first floor elevation above ground, and the number of stories. In this case, the presence of critical assets in first floors is also a key characteristic (this is important for critical facilities such as hospitals). However, in addition to the effects of flooding, tsunamis also carry a component of lateral force (flow) which can cause further structural damage. This also applies to bridges, where a tsunami may cause structural damage to the foundation, piles or abutments. Hence, the structural system (e.g., the number of spans and the presence of piers) and freeboard height are characteristics that indicate vulnerability. Flooding may structurally damage the road base structure, eroding or washing away embankments. Water and sanitation infrastructure are in general not too vulnerable, but pipes that are designed to work unpressurized might suffer damages if they become pressurized.

Details on the application of the two vulnerability assessment methods (detailed structural modeling and topological assessment) are described below.

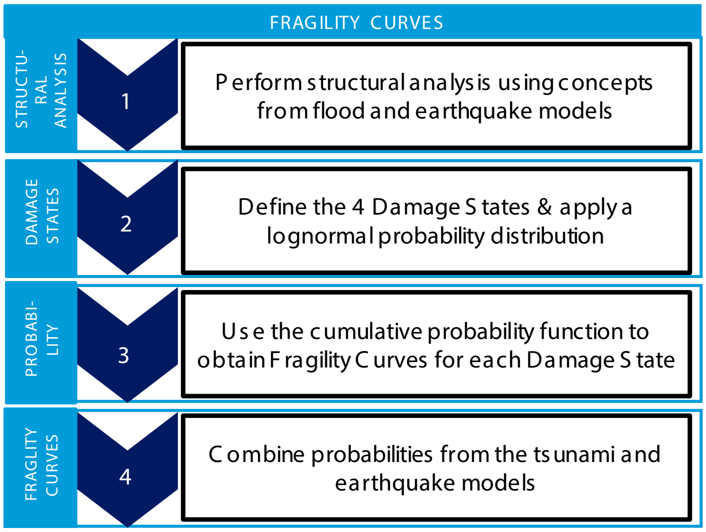
Detailed structural modeling (for individual assets): In general, the response of the infrastructure to tsunami waves and flooding must be analyzed using engineering techniques specific for the type of infrastructure. Structural reliability theory may be applied as well to perform these analyses. Structural analyses may be performed using empirical or analytical data to establish what levels of damage and relative loss (losses relative to the cost of replacing the structure) go with increasing levels of flooding height and flow velocity.

To do this, three main approaches can be used: applying structural reliability theory, using the Hazus approach of generating fragility curves (FEMA, 2017), and using the CAPRA approach of generating vulnerability curves (ERN-AL, n.d.e). Both fragility curves and vulnerability curves should be constructed as a function of water height (m), water flow velocity (m/s), or flux (velocity squared multiplied by water depth - m^3/s^2).

a. For the first approach, structural reliability theory is applied to the detailed structural analyses to ultimately calculate probabilities of failure or collapse (see Franchin et al., 2012; Lazar and Dolsek, 2012; Todinov, 2008; Wayan, 2012).

b. For the second approach (fragility curves), Figuire 6.27 summarizes the process of constructing these curves (see FEMA, 2017; NGI and GA, 2015; Suppasri et al., 2013).

Figure 6.27. Procedure to Construct Fragility Curves



1. A structural analysis method is selected to model the structure's behavior and response to tsunami flooding and lateral forces. Damage to (i) the structural system, (ii) non-structural components, and (iii) contents is evaluated. Separate analyses are made for (i) tsunami flooding and (ii) tsunami-induced lateral forces (flow). For the former, data and methods used on the Hazus Flood Model are used, complemented with a more theoretical and analytical approach, to estimate the damage to non-structural components and contents. For the latter, engineering concepts from (i) FEMA-P646 Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA, 2012), (ii) the capacity curve approach used in the Hazus Earthquake Model engineering, and (iii) the flood loads of ASCE 7-10 (ASCE, 2010) are used to estimate the structural damage.

2. For the case of tsunami inundation, the median damage values for each damage state are modified from the basic flood model using equations that convert from other types of flooding to tsunami flooding. For the case of tsunami flow, capacity curves from the earthquake model are used and harmonized for tsunami lateral forces. From both of these processes, damage states are established for each case. As a result, the four damage states (none, moderate, extensive, and complete) are represented by threshold water height values for tsunami flooding and by threshold momentum flux values for tsunami flux. A log-normal probability distribution is then assigned to the damage states for which the relevant statistical moments are determined (median and standard deviation) and the distribution parameters computed.

3. The cumulative probability function representing the probability of being or exceeding a particular damage state becomes the fragility function. Four fragility functions are obtained, one for each damage state (none, moderate, extensive, and complete damage states). Separate fragility curves result for (i) tsunami flooding as a function of inundation height in meters and (ii) tsunami flow as a function of momentum flux in m^3/s^2. Discrete probabilities of being exactly in a particular damage state can then be computed from these curves and stored in what is called the damage probability matrix.

4. Combine damage state probabilities from the tsunami and earthquake vulnerability models without double counting.

c. For the third approach, the same method used for other types of flooding (see section above) can be applied as well for tsunami. Hence, vulnerability curves for the specific infrastructure under analysis may be created using empirical or analytical data to establish what levels of damage and relative loss (losses relative to the cost of replacing the structure) go with increasing levels of flooding height. To account for the torrential flooding that induce later forces, the velocity of the flow is relevant as well, and thus the created vulnerability curves should also reflect relative damage in response to flow velocity (see Cardona et al., 2015; ERN-AL, n.d.e; Maqsood et al., 2014; NGIandGA, 2015).

For a probabilistic risk assessment (and using a corresponding probabilistic hazard assessment), any of the three approaches detailed above provides the required probabilistic treatment of the vulnerability component. This vulnerability approach should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment (and using a corresponding deterministic hazard assessment), mean damage values or damage states estimated after performing the structural analysis may be assumed as certain (with no consideration of uncertainty). As a result, the structure's behavior is taken directly from the structural analyses, which in turn are performed for a single (and assumed as certain) tsunami flooding and flow solicitation and without considering uncertainty in the engineering problem or design. This vulnerability approach should be used with the deterministic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a deterministic risk assessment.

Topological assessment (for multiple assets): Existing fragility and/or vulnerability functions should be used. Using the abovementioned characteristics that determine tsunami vulnerability, damage functions which are adequate for the existing different typologies of structures should be identified. Table 6.6 provides available vulnerability and fragility function resources (Maqsood et al., 2014; Suppasri et al., 2013). If the exposure database is spatially individualized (even though the assets are grouped by typologies, individual assets, for example, building by building, are still identified and assigned a typology), then each individual structure must have an assigned curve. If the exposed assets were further aggregated spatially (e.g., into blocks, neighborhoods, or municipalities), instead of assigning curves to individual structures, the building types are grouped by square footage and vulnerability or fragility functions are assigned to the grouped units representing the average or most representative topology present within.

For a probabilistic risk assessment, the selected fragility and/or vulnerability curves must be used with their complete probabilistic representation (for vulnerability curves this means including the standard deviation function as well into the risk calculations). This vulnerability approach should be used with the probabilistic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment, mean damage values or damage states may be used from the vulnerability and/or fragility curves. This vulnerability approach should be used with the deterministic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a deterministic risk assessment.

To determine percentage loss values associated with different damage states and typology, Table 6.12 may be used. To create or assign loss-of-use functions, use the general values given by Table 6.7 according to approximate damage states for various sectors.

Table 6.12. Tsunami Structural and Non-Structural Losses Based on Damage State Probabilities and Occupancy Types

	Structural			Non-Structural		
Occupancy	Moderate	Extensive	Complete	Moderate	Extensive	Complete
Agriculture	0.046	0.231	0.462	0.054	0.176	0.538
Retail Trade	0.029	0.147	0.294	0.071	0.267	0.706
Parking	0.061	0.304	0.609	0.039	0.152	0.391
Wholesale Trade	0.032	0.162	0.324	0.068	0.256	0.676
Personal and Repair Services	0.016	0.081	0.162	0.084	0.319	0.838
Professional/Technical Services	0.019	0.096	0.192	0.081	0.308	0.808
Banks	0.014	0.069	0.138	0.086	0.327	0.862
Hospital	0.014	0.07	0.14	0.086	0.328	0.86
Medical Office/Clinic	0.014	0.072	0.144	0.086	0.325	0.856
Entertainment & Recreation	0.01	0.05	0.1	0.09	0.341	0.9
Theaters	0.012	0.061	0.122	0.088	0.334	0.878
Grade Schools	0.019	0.095	0.189	0.081	0.34	0.811
Colleges/Universities	0.011	0.055	0.11	0.089	0.387	0.89
General Services	0.018	0.09	0.179	0.082	0.312	0.821
Emergency Response	0.015	0.077	0.153	0.085	0.322	0.847
Heavy	0.016	0.078	0.157	0.084	0.277	0.843
Light	0.016	0.078	0.157	0.084	0.277	0.843
Food/Drugs/Chemicals	0.016	0.078	0.157	0.084	0.277	0.843
Metals/Minerals Processing	0.016	0.078	0.157	0.084	0.277	0.843
High Technology	0.016	0.078	0.157	0.084	0.277	0.843
Construction	0.016	0.078	0.157	0.084	0.277	0.843
Churches and Other Non-profit Org.	0.02	0.099	0.198	0.08	0.306	0.802
Single Family Dwelling	0.023	0.117	0.234	0.077	0.33	0.766
Manuf. Housing	0.024	0.073	0.244	0.076	0.302	0.756
Duplex	0.014	0.069	0.138	0.086	0.344	0.862
Triplex / Quads	0.014	0.069	0.138	0.086	0.344	0.862
Multi-dwellings (5 to 9 units)	0.014	0.069	0.138	0.086	0.344	0.862
Multi-dwellings (10 to 19 units)	0.014	0.069	0.138	0.086	0.344	0.862
Multi-dwellings (20 to 49 units)	0.014	0.069	0.138	0.086	0.344	0.862
Multi-dwellings (50+ units)	0.014	0.069	0.138	0.086	0.344	0.862
Temporary Lodging	0.014	0.068	0.136	0.086	0.346	0.864
Institutional Dormitory	0.019	0.094	0.188	0.081	0.324	0.812
Nursing Home	0.018	0.092	0.184	0.082	0.326	0.816

	Contents			Inventory		
Occupancy	Moderate	Extensive	Complete	Moderate	Extensive	Complete
Agriculture	0.05	0.25	1	5	25	50
Retail Trade	0.05	0.25	1	5	25	50
Parking	0.05	0.25	1			
Wholesale Trade	0.05	0.25	1	5	25	50
Personal and Repair Services	0.05	0.25	1			
Professional/Technical Services	0.05	0.25	1			
Banks	0.05	0.25	1			
Hospital	0.05	0.25	1			
Medical Office/Clinic	0.05	0.25	1			
Entertainment & Recreation	0.05	0.25	1			
Theaters	0.05	0.25	1			
Grade Schools	0.05	0.25	1			
Colleges/Universities	0.05	0.25	1			
General Services	0.05	0.25	1			
Emergency Response	0.05	0.25	1			
Heavy	0.05	0.25	1	5	25	50
Light	0.05	0.25	1	5	25	50
Food/Drugs/Chemicals	0.05	0.25	1	5	25	50
Metals/Minerals Processing	0.05	0.25	1	5	25	50
High Technology	0.05	0.25	1	5	25	50
Construction	0.05	0.25	1	5	25	50
Churches and Other Non-profit Org.	0.05	0.25	1			
Single Family Dwelling	0.05	0.25	1			
Manuf. Housing	0.05	0.25	1			
Duplex	0.05	0.25	1			
Triplex / Quads	0.05	0.25	1			
Multi-dwellings (5 to 9 units)	0.05	0.25	1			
Multi-dwellings (10 to 19 units)	0.05	0.25	1			
Multi-dwellings (20 to 49 units)	0.05	0.25	1			
Multi-dwellings (50+ units)	0.05	0.25	1			
Temporary Lodging	0.05	0.25	1			
Institutional Dormitory	0.05	0.25	1			
Nursing Home	0.05	0.25	1			

Source: Hazus 4.2 (2018).

6.1.4.4.8 Volcanoes

For ashfall, the main characteristic comes down to the type and material of the roof, which determines a structure's roof load bearing capacity. For lava and mudflows, the characteristics include structural typology or structural system and the material.

Detailed structural modeling (for individual assets): It is not very common to construct or find damage functions for the different volcanic sub-hazards including ashfall, lava flows, and pyroclastic flows (or mudflows). However, the CAPRA platform provides simplified approaches to create vulnerability functions for these sub-hazards (see ERN-AL, n.d.e).

For ashfall, it is assumed that the relative damage follows a Beta distribution, and thus this probability distribution is assigned, and vulnerability functions are created in terms of total ash depth (ash accumulation). These will vary depending on the type of structure and the type of roof, considering the roof's load capacity (see ERN-AL, n.d.e).

For the case of the more destructive sub-hazards of lava and pyroclastic flows, a simple approach is used where the vulnerability functions are assumed as binary: if the structure is exposed to an area of high probability of impact from these sub-hazards, then the damage will be total (relative damage of 100 percent), otherwise the damage will be zero (relative damage of 0 percent) (see ERN-AL, n.d.e).

For a probabilistic risk assessment (and using a corresponding probabilistic hazard assessment), the approach mentioned above provides the required probabilistic treatment of the vulnerability component. This vulnerability approach is not very common, but if it is used it should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment (and using a corresponding deterministic hazard assessment), mean damage values or damage states estimated may be assumed as certain (with no consideration of uncertainty). This vulnerability approach should be used with the deterministic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a deterministic risk assessment.

Topological assessment (for multiple assets): Although rare, use existing vulnerability functions. Using the abovementioned characteristics that determine vulnerability to volcanic hazards, identify damage functions which are adequate for the existing different typologies of structures. Table 6.5 provides available vulnerability function resources. If the exposure database is spatially individualized (even though the assets are grouped by typologies, individual assets, for example, building by building, are still identified and assigned a typology), then each individual structure must have an assigned curve. If the exposed assets were further aggregated spatially (e.g., into blocks, neighborhoods, or municipalities), instead of assigning curves to individual structures, the building types are grouped by square footage and vulnerability functions are assigned to the grouped units representing the average or most representative topology present within.

For a probabilistic risk assessment, the selected vulnerability curves must be used with their complete probabilistic representation (for vulnerability curves this means including the standard deviation function as well into the risk calculations). This vulnerability approach should be used with the probabilistic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment, mean damage values or damage states may be used from the vulnerability curves. This vulnerability approach should be used with the deterministic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a deterministic risk assessment.

To create or assign loss-of-use functions, the general values given in Table 6.7 should be used according to approximate damage states for various sectors.

6.1.4.4.9 Wildfire

For fire in general, the main characteristic are the material, which determines if an element is flammable or not. This applies to buildings, bridges, pipes, and other infrastructure. Typically, fire safety and protection are well embedded in structural engineering of steel structures. See ASCE/SEI 7-10 (ASCE, 2010) and ASCE/SEI 7-16 (ASCE, 2016) for more details.

Detailed structural modeling (for individual assets): In general, the response of the infrastructure to fire must be analyzed using engineering techniques specific for the type of infrastructure. Structural reliability theory may also be applied to perform these analyses. Because historically this hazard has not had the same treatment as the rest in terms of its incorporation into well-established risk models and assessments, it is not common to find methods to build fragility or vulnerability curves. However, recently researchers have started to develop these methods (Gernay et al., 2015; 2016; 2018; Khorasani et al., 2016).

For a probabilistic risk assessment, the vulnerability assessment has to be done probabilistically as well, using structural reliability of building fragility curves that consider this. This vulnerability approach should be used with the probabilistic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment (and using a corresponding deterministic hazard assessment), mean damage values or damage states estimated after performing the structural analysis for a particular fire scenario may be assumed as certain (with no consideration of uncertainty). As a result, the structure's behavior is taken directly from the analyses, which in turn are performed for a single (and assumed as certain) fire scenario and without considering uncertainty in the engineering problem or design. This vulnerability approach should be used with the deterministic hazard assessment approach and with the detailed – individual assets exposure approach to obtain a deterministic risk assessment.

Topological assessment (for multiple assets): although not very common, use existing fragility functions. Using the abovementioned characteristics that determine fire vulnerability, identify damage functions which are adequate for the existing different typologies of structures (see Gernay et al., 2015; 2016; 2018; Khorasani et al., 2016). If the exposure database is spatially individualized (even though the assets are grouped by typologies, individual assets, for example, building by building, are still identified and assigned a typology), then each individual structure must have an assigned curve. If the exposed assets were further aggregated spatially (e.g., into blocks, neighborhoods, or municipalities), instead of assigning curves to individual structures, the building types are grouped by square footage, and vulnerability functions are assigned to the grouped units representing the average or most representative topology present within.

For a probabilistic risk assessment, the selected fragility curves must be used with their complete probabilistic representation. This vulnerability approach should be used with the probabilistic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a probabilistic risk assessment.

For a deterministic risk assessment, mean damage values or damage states may be used from the structural analyses. This vulnerability approach should be used with the deterministic hazard assessment approach and with the proxy – aggregated assets exposure approach to obtain a deterministic risk assessment.

To create or assign loss-of-use functions, the general values given in Table 6.7 should be used according to approximate damage states for various sectors.

6.1.4.4.10 Vulnerability considerations during the construction phase of a project

Table 6.13 gives guidance on general requirements to assess a project's vulnerability during the construction phase.

Table 6.13. Vulnerability Assessment Approach Requirements (construction phase)

Hazard of concern	Approach	Vulnerability data requirements
Flood, surge, tsunami, landslide, volcano, and wildfire	Exposure	• Locations of equipment and materials, and identification of required roads, rail, and utilities. • Employee and community demographic information and assumptions. • Community or site environmental assets, hazmat locations and quantities.
Earthquake and hurricane wind	Exposure	• Storage of equipment and materials, and identification of required roads, rail, and utilities. • Employee and community demographic information and assumptions. • Community or site environmental assets, hazardous material (hazmat) locations and quantities.
Drought	Exposure	• Equipment and materials requiring water. • Employee and community demographic information and assumptions. • Community or site environmental assets, hazmat locations and quantities.
Heat wave	Exposure	• Equipment and materials sensitive to heat. • Employee and community demographic information and assumptions. • Community or site environmental assets, hazmat locations and quantities.

Table 6.13. Vulnerability Assessment Approach Requirements (operational phase)

Hazard of concern	Approach	Vulnerability data requirements
Wildfire	Site level, detailed	· Specific flame height damage functions for detailed building characteristics.
Landslide	Site level, detailed	· Specific land volume damage functions for detailed building characteristics.
Volcano	Site level, detailed	· Specific land volume damage functions for detailed building characteristics.

6.1.5 Analysis of Risk Results

6.1.5.1 General considerations to analyze risk results

The most important part of conducting a risk assessment comes after having quantified the risk using any of the methods presented above: analyzing the results. This analysis should carefully look at risk (losses) in absolute and relative terms, as well as at grouped and disaggregated results (i.e., by categories) and at the spatial distribution of the risk, if applicable.

Table 6.14 presents some examples of hazard-specific aspects to keep in mind when analyzing the results from the risk assessment. These are intended to guide the thinking process when evaluating and analyzing results and includes general topics that may be relevant to each hazard. Furthermore, Table 6.15 provides guidance on the basic questions that should be asked to evaluate the results of a risk assessment. These are useful to think about and include in the Disaster and Climate Change Risk Management Planwhich is discussed next in Section 6.1.7.

Table 6.14. Risk Results Analysis - General Considerations Based on Hazard

Hazard of Concern	Considerations to keep in mind for the analysis of results
Flood (all types)	• Check transportation routes (especially bridges) for flooding. • Check asset storage areas (for cars, city buses, products, or others) for flooding • Review expected debris areas to ensure project can operate.
Hurricane wind	• Review expected debris areas to ensure project can operate.
Landslide	• Review expected debris areas to ensure project can operate.
Wildfire	• Check transportation routes exposed to wildfire.
Drought	• Determine water supply vs. demand for project and area.
Volcano	• Check transportation routes for lahar flow, ash, and lava. • Review expected debris areas to ensure project can operate.
Earthquake	• Check transportation routes (especially bridges) for damage and functionality. • Review expected debris areas to ensure project can operate.
Heat Wave	• Identify equipment and products susceptible to heat. • Estimate an increase in power demand during events (connected to low water availability) • Identify potential for heat-related illness.

Table 6.15. Guiding Questions to Evaluate a Risk Assessment

Guiding questions
Have all natural hazards that can potentially affect the project been identified?
Have past events been identified?
Have all the natural hazards been adequately evaluated? Has the intensity, frequency (only for probabilistic assessments) and spatial extent been properly determined?

Guiding questions
Has the effect of climate change on natural hazards been identified and evaluated?
Has the baseline exposure been adequately characterized? (for assets and population)
Has the post-project intervention exposure been adequately characterized? (for assets and population)
Has the physical and social vulnerability of the project and surrounding communities been characterized?
Has the risk been adequately calculated for the baseline conditions?
Has the risk been adequately calculated for the post-project intervention conditions and for any proposed alternatives or proposed measures?
Does the project create additional risk (incremental risk) to the community or environment?
Will climate change increase the risk and how significantly?
What is the tolerable risk for the project? (this is a decision, so who makes that decision for the project?)

6.1.6 Evaluation and prioritization of risk reduction measures and Disaster and Climate Change Risk Management Plan

One of the most powerful devices that a quantitative risk assessment provides, aside from making the risk truly visible and tangible, is the ability to rationally evaluate the implications for risk of different project alternatives or risk-reduction measures through a technically backed and tangible quantitative evaluation. These evaluations of options are then used to inform a disaster risk management plan (DRMP) that will help reduce and manage the risk to the project as well as the potential risk caused to third parties by the project. The tools and methods described in this section for the evaluation of risk-reduction measures (as well as project alternatives) can be directly used in conjunction with the risk assessment methods described above.

To identify and assess risk mitigation options, three tasks will be undertaken. The first is identifying structural and non-structural options to mitigate the risk associated with a specific hazard. The second involves identifying approach(es) to assess the risk mitigation options for your project based on their effectiveness and determine which one(s) are feasible. The third involves preparing a DRMP.

6.1.6.1 Identify risk mitigation options

This section provides guidance on identifying risk-mitigation options. Different types of risk mitigation options are discussed below, and several specific examples are provided in Appendix G. For the purposes of consistency and ease of reference in this Methodology, the term risk mitigation is used to refer to any measure that reduces disaster and climate change risk due to natural hazards and is considered synonymous with climate change adaptation (see Appendix B for the definition of terms used in this guidance).

First, as many risk mitigation options as possible should be identified. It is important to become familiar with the types of risk-mitigation options available. For this Methodology, the risk-mitigation options have been categorized as: (i) strengthening, (ii) protection and control, (iii) planning, (iv) natural systems protection, (v) education and awareness, and (vi) preparedness and response. It is common to mitigate risk from a natural hazard by combining different options to ensure risk reduction. These risk-mitigation options, including structural and non-structural measures, or a combination of these, are described below.

6.1.6.1.1 Structural measures

Strengthening Options:

These options involve modifying existing structures and infrastructure or designing new projects to ensure that they are structurally resilient to specific hazards (i.e., improving a structure's vulnerability) or removing them from the hazard-prone area (i.e., altering their exposure). It is important to consider these options during the design stage; generally, they can be cost effective to integrate into a design but can be very costly to implement after a project has been constructed. Examples of strengthening options include:

- Define project siting (moving a structure out of a hazard-prone area)
- Undergrounding utilities
- Structural retrofitting
- Elevating a structure
- Adopting resilient building standards in the design

Protection and Control Options:

These measures focus on protecting structures by erecting barriers and deflecting destructive forces. Examples of protection and control options include:

- Levees
- Discharge channels
- Seawalls
- Slope/ground stabilization works

These types of measures could also include nature-based protection (e.g., protective vegetation). Natural systems protection options are used to minimize damage and loss, and also preserve or restore the functions of natural systems. Examples of natural system protection include:

- Sediment and erosion control
- Stream corridor restoration
- Forest management
- Wetland restoration and preservation

6.1.6.1.2 Non-Structural measures

Planning and Institutional Options:

Local land use or comprehensive plans embody the goals, values, and aspirations of the community. Plans should identify current development patterns and trends as well as areas where future development should and should not occur. Plans should include policies and ordinances that steer development away from hazard-prone areas, such as floodplains, to avoid putting people and property at risk. Planners should coordinate in preparing plans to ensure consistency across plans. Examples of planning options include:

- Land use ordinances
- Open-space preservation
- Stormwater management plan
- Education and Awareness Program Options:

These options are used to inform and educate owners, renters, operators, and government officials about hazards and risk and potential ways to mitigate them. Although this type of risk mitigation measure reduces risk less directly than structural measures, it is an important foundation. A greater understanding and awareness of hazards and risk by everyone is more likely to lead to direct actions. Examples of education and awareness programs include:

- Presentations to utility operators or others
- Outreach to residents or tenants in hazard-prone areas
- Training on construction best practices for risk mitigation
- Real estate disclosure

Preparedness and Response Options:

These options help organizations and communities prepare for and respond to a disaster. Although the goal of the previous risk-mitigation options is to reduce risk, there will always be some residual risk which can be managed by preparing people for a disaster. Examples of preparedness and response actions include:

- Developing and testing (though simulations and drills) business continuity plans to ensure that the critical functions of the structure remain operational or are quickly restored after the hazard event.
- Installing early warning systems that prevent the loss of human life and injuries in disaster scenarios where the size of the hazard event has overcome structural mitigation measures.
- Awareness campaigns to inform employees, operators, and the population at risk of available shelter locations during and following a hazard event.
- Developing and testing (through drills) contingency plans that include evacuation activities.

Appendix G contains other risk-mitigation options. The project types considered in that appendix have detailed risk mitigation options; even if your project type is different, you should still be able to get ideas from these.

6.1.6.2 Analyze Risk-Mitigation Options

To select the most appropriate risk-mitigation options, it is necessary to: (i) calculate its benefit in terms of its effectiveness at reducing the risk, (ii) calculate the cost of implementation and maintenance, and (iii) compare the costs and benefits using one or several economic analysis tools to present the merits of including each mitigation option in the DRMP.

Calculate Mitigation Option Benefits:

To evaluate the effectiveness of a mitigation option, the extent to which it achieves its intended goals (mitigation of hazard risk) must be analyzed. This step should include analyzing the effects of the mitigation option at the same level of detail and by applying the same risk assessment methodology that was employed in the quantitative risk assessment. Table 6.16 summarizes this process by risk assessment methodology.

Table 6.16. Quantifying Measure Benefits by Risk Assessment Methodology

Risk assessment methodology	Description
Probabilistic risk assessment	Risk-mitigation options should be evaluated at the same level of detail as employed in the initial disaster risk assessment (i.e., without implementation of the option). This requires updating the modeling to incorporate the changes that occur with implementation of the option and running the models again to assess effects. Outputs will be estimates of AAL (for simplifiedprobabilistic) and LEC and PML (for fully probabilistic) with the option in place. The remaining estimated risk values with the option in place represents residual risk (risk not prevented by the option). The difference between these values with and without the mitigation option is the mitigation option's benefits (losses prevented).
Deterministic risk assessment	Risk-mitigation options should be evaluated at the same level of detail as employed in the initial risk assessment (i.e., without implementation of the option). This requires updating the modeling to incorporate the changes that occur with implementation of the option and running the model again to assess effects. Because the deterministic assessment evaluates individual hazard events, benefit estimates represent the losses expected to be prevented from that one event if a mitigation option was in place.
Robust Decision Making (RDM)	Multiple options are inherently tested within the RDM process under a wide range of possible configurations or "futures." Benefits are understood in terms of the ability of a measure to meet the desired goal. In the first step of RDM, a set of metrics that reflect the desired goals is defined through deliberation with stakeholders. Thus, these metrics will vary from case to case and will reflect project-specific goals and measures of success.
Exposure assessment	Options should be evaluated at the same level of detail as employed in the exposure assessment without implementation of the option. This requires updating the hazard modelling and exposure mapping exercise to incorporate the changes that occur with implementation of the option. The effects of mitigation options can be quantified in terms of changes in the geographic areas susceptible to hazard impacts and/or the changes in assets exposed to hazard impacts. For example, effects of a floodwall measure would be quantified by delineating the revised extent of inundation with the floodwall in place, and then tabulating the reduction in assets exposed to impact.

Calculate Mitigation Option Costs:

The next step is to estimate the costs of implementing each mitigation option, including both upfront implementation costs and operating and maintenance costs over a defined period of analysis. Cost information should be developed to a planning level and can be based upon quantity calculations and industry standard unit costs. Construction costs should also include planning, engineering, and design costs, as well as supervision and administration costs, and an allowance for contingencies. Other project costs such as real estate costs and expected operating and maintenance streams should also be included. Costs for infrastructure projects are typically developed in current price levels over a 50-year planning horizon and are presented in present values. It is important to document all price components considered, and the price level, period of analysis, and discount rate used to compute present values to inform decision makers about the economic factors used in the analysis.

Some non-structural options may not require quantities to be calculated but should be developed with a similar level of consideration for all costs associated with the action. For example, costs for a community-based early warning and response system should consider not only costs for development and deployment, but other costs as well, such as equipment maintenance and upgrade, staff, and public training sessions, public feedback mechanisms, and iterative updates to incorporate new development or redevelopment in the community.

Compare Mitigation Option Costs and Benefits:

The third step in analyzing a mitigation option is to select the appropriate methodology for comparing the costs and benefits of the option. Economic methodologies of benefit-cost analysis (BCA) and cost effectiveness analysis (CEA) can provide information to help decision makers assess the merits of a proposed mitigation option.

When the effectiveness of a proposed mitigation option can be measured in monetary terms, BCA can be applied to assess the economic efficiency and effectiveness of the option. In cases where the effectiveness of a proposed option can only be evaluated in non-monetary but quantitative terms, CEA can be applied to make economically informed decisions. Both these methodologies are described further in the following sections.

An additional methodology for comparing project benefits and costs is called multi-criteria analysis (MCA). MCA is a method of analyzing mitigation options when it is desirable to include more than one benefit metric and retain transparency in the weighting of those metrics. MCA is a structured methodology for identifying criteria and weights, scoring measure performance for each criterion and ranking the measures in order of weighted contribution to the criteria. MCA can foster stakeholder engagement in the DRMP formulation and evaluation process. MCA can stand alone but is often a complement to either a BCA or a CEA. Table 6.17 summarizes the economic and MCA analyses included in this Methodology, their applicability to the risk assessment methodologies, and the output metrics associated with each analysis. Each of these analyses is discussed further in the subsections that follow that table.

Table 6.17. Economic and MCA Analyses for Risk Assessment Methodologies

Risk Assessment Methodology	Applicable Analyses
Probabilistic risk assessment	**<u>Cost-Benefit Analysis</u>**: CBA can provide decision support data such as net present value/ return on investment, benefit to cost ratio, and residual losses. • Net present value measures the extent to which the mitigation option generates a positive return on investment. It is calculated as the present value of the discounted flows of project costs and benefits over the planning horizon. • CB ratio is the ratio of expected project benefits to costs and is calculated by dividing the present value of avoided losses (benefits) by the present value of mitigation option costs. A CB ratio greater than 1.0 indicates that mitigation option benefits exceeds its costs. • Residual losses are the average annualized losses that would still be expected to remain with the mitigation option in place. It is important to communicate this residual risk so decision makers and the population living in the influence area understand that the mitigation option does not eliminate all risks.
	<u>Multi-Criteria Analysis:</u> Optional complementary analysis which can incorporate into the planning process some criteria that may be important to stakeholders but not included in monetary metrics applied to represent intended mitigation option benefits. Examples could include unintended effects of the mitigation option that would be important to decision makers or affected stakeholders.

Risk Assessment Methodology	Applicable Analyses
Deterministic risk assessment	**Abbreviated Cost–Benefit Analysis:** While not as robust as the cost–benefit analysis based on probabilistic analysis, it is possible to compare mitigation option costs with the expected damages from a past known or worst-case hazard events. This abbreviated CBA can provide decision support data such as an avoided loss point estimate or a residual losses point estimate. • Avoided Loss Point Estimate: For a single event, estimate the total losses that could have been avoided with the mitigation option in place. • Residual Losses Point Estimate: For a single event, estimate the total losses that would still be expected to occur with the mitigation option in place.
	Multi-Criteria Analysis: Optional complementary analysis which can incorporate into the planning process some criteria that may be important to stakeholders but not included in monetary metrics applied to represent intended mitigation option benefits. Examples include unintended effects of the mitigation option that would be important to decision makers or affected stakeholders.
Exposure Assessment	Cost-Effectiveness Analysis: For each mitigation option under consideration, compare the costs of the plan with the quantified exposure reduction based upon the quantified exposure analysis metric applied in in the exposure assessment without the mitigation option. Then quantify the beneficial or adverse changes that would occur in asset exposure with the mitigation option. Quantified risk reduction metrics could include values such as reduction in area at risk, reduction in population at risk, or reduction in assets at risk. Provide a qualitative assessment and justification of if/why the risk reduction is worth the cost for decision makers.
	Multi-Criteria Analysis: Use the variables from the exposure assessment as criteria in the MCA along with additional qualitative criteria that may be important to stakeholders but not included in monetary metrics applied to represent intended mitigation option benefits. Score each measure's criteria performance based upon the change in asset exposure to generate a ranking of measures.

6.1.6.2.1 Cost–Benefit Analysis

CBA can be applied for all benefits and costs measured in a common monetary unit. All costs and benefits should be evaluated over a common period of analysis. Streams of monetary costs and benefits over the period of analysis are converted to their present value using a common discount rate for comparison in CBA.

It is recommended that the period of analysis for CBA under this program be set at a timeframe that is aligned with the project's lifespan, which can vary according to the type of project. The period of analysis for each CBA will begin at the base year and extend out 50 years for analysis of streams of mitigation option benefits and costs. The base year should be set as the year that construction is complete.

The recommended steps for conducting a CBA are as follows:

1. Evaluate monetary mitigation option risk reduction benefits over the period of analysis

2. Evaluate life cycle monetary costs over the period of analysis

3. Convert all cost and benefit streams to their present value (PV)

4. Calculate net benefits as the difference of the PV of benefits and costs over the period of analysis

5. Calculate benefit to cost ratio as the PV of benefits over the period of analysis divided by the PV of costs over the period of analysis

6. Evaluate uncertainties

7. Present information for decision making

The following is a description of these steps in more detail:

1. Evaluate Monetary Mitigation Option Risk Reduction Benefits

The intended benefit of implementing a mitigation option is the resulting reduction in risk. Evaluating risk reduction requires the estimation of the risk both with and without the mitigation option. The estimate of monetary risk with the mitigation option should be derived using the same risk assessment methodology as employed in the model configuration without the mitigation option. The difference between both calculations (with and without mitigation) is the benefit of the mitigation option. The remaining risk after implementing the mitigation option is called the residual risk. For a probabilistic risk assessment, the benefit of risk reduction (avoided losses) can directly be taken from the AALs, which will result in having annualized benefits that can be incorporated in the life cycle analysis. For a deterministic analysis, only the avoided losses for a particular event will be obtained.

2. Evaluate Life Cycle Monetary Costs

Just as with mitigation option benefits, costs can occur over the entire period of analysis. Planning, engineering design, real estate acquisition, and construction costs typically occur prior to or in the base year. Operation, maintenance, repair, replacement, and rehabilitation costs may occur at various moments over the period of analysis. It is important to forecast and estimate all the expected streams of mitigation option costs for inclusion in the BCA.

3. Calculate Present Value of All Cost and Benefit Streams

To compare streams of benefits and costs on equal terms, a common price level is required. Price level refers to the average cost of goods and services in an economy at a specified time. Since the period of analysis spans many years, price level will not remain constant. Rather than forecast price level changes over the period, a single price level is selected for the CBA. Because estimates of benefits and costs are more easily developed in current prices, the analysis price level should be set at the current price level (year in which analysis is performed) and that price level applied for all costs and benefits over the period of analysis.

Next, the streams of cost and benefits must be discounted. Discounting adjusts future sums of money to reflect the time value of money. The principle behind the notion of time value of money is that a dollar received today has greater value than a dollar received in the future. For the CBA, the ratio of how much more a dollar received today is worth than a dollar received in the future is the discount rate. The discounted value of a future sum is called its present value. The formula for present value of a future sum is given by:

$$PV = \frac{S}{(1+r)^t}$$

Where *S* is the future sum, *r* is the discount rate, and *t* is the year of the period of analysis.

For a probabilistic risk assessment, the annualized avoided losses (taken from the AALs) allow for a direct application of a life cycle analysis and calculation of the *PV* with a discount rate.

A low discount rate means that the value of benefits and costs occurring in future periods are minimally reduced relative to a high discount rate, where the value of future benefits and costs are greatly reduced compared to their value if they occurred today.

4. Calculate Net Benefits

Net benefits, or net present value, refer to the balance of project benefits versus costs. Like the previous step, streams of future payments must be discounted. Net benefits are estimated by calculating the net present value of costs and benefits, or sum of the discounted balance of costs and benefits during each period of the analysis.

$$PV_{\text{Net Benefits}} = PV_{\text{Benefits}} - PV_{\text{Costs}}$$

5. Calculate Benefit-to-Cost Ratio

The benefit-to-cost ratio (BCR) is a metric used to describe the relative magnitude of benefits and costs. A BCR of 1.0 indicates that the present value of benefits equals the present value of costs. A BCR over 1.0 indicates that benefits exceed costs, and a BCR under 1.0 indicates that costs exceed benefits.

$$BCR = PV_{\text{Benefits}} / PV_{\text{Costs}}$$

6. Evaluate Uncertainties

Estimation of the costs and benefits associated with a project is subject to multiple sources of uncertainty that might affect the computed net benefits and benefit-to-cost ratio. At a minimum, key sources of uncertainty should be considered and described in terms of their magnitude to provide decision makers with a complete picture of the planning context.

For a probabilistic risk assessment, uncertainty was already acknowledged and incorporated in the risk calculations performed to obtain the AALs; the AAL is a statistical quantity, the expected value of a joint probability distribution function. Hence, the measure of dispersion of the loss (standard deviation) can also be determined from the risk assessment. Consequently, the benefits, which are avoided AALs (AAL without mitigation option – AAL with mitigation option), already incorporate uncertainty. On the other hand, for deterministic risk assessment, the benefits do not carry uncertainty.

Thus, quantitative incorporation of uncertainty into the BC analysis may also be guaranteed depending on the nature of the project and the necessary level of certainty in the benefit calculations for decision makers to move forward. Quantitative uncertainty analyses can range in complexity depending on the needs of the project, from simple scenario analysis to additional statistical modeling to develop parameters of uncertainty on estimates of project net present value and/or the BCR.

A simple sensitivity scenario analysis might include varying the estimated benefits and costs up or down to identify the point at which net benefits fall to zero, e.g., BBR drops to 1.0 (would work with a deterministic risk assessment). A more detailed statistical analysis, compatible with a probabilistic risk assessment, could incorporate the uncertainty from the AALs, as well as develop a probability distribution to represent costs. These inputs could feed a Monte Carlo simulation to develop estimates of net benefits and the BCR with uncertainty parameters. This would enable questions like "How likely is it that the BCR will exceed 1.0?" to be answered.

7. Present Information for Decision Making

Risk communication is a critical component of the BCA. Results should be presented in a narrative that should describe the planning context and explain key outputs of the analysis with a level of detail appropriate to the intended audience. Information in the BCA narrative should address the following:

Project name and location and expected project timeline

a. Identified natural hazards

b. Description of risk mitigation option

c. Date of BCA

d. Base year for analysis

e. Period of analysis

f. Discount rate

g. Risk without mitigation option

h. Residual risk with mitigation option

i. PV of mitigation option benefits

j. PV of mitigation option costs

k. Net benefits

l. Benefit–cost ratio

m. Uncertainty

6.1.6.2.2 Cost-Effectiveness Analysis

Like a CBA, a CEA provides a structured analytical framework for evaluating the degree to which a mitigation option would achieve its objectives (benefits) and the financial resources required for designing, implementing, and operating the mitigation option (costs). CEA is a useful economic tool for comparing the costs and benefits of mitigation options when information is not available to support the monetary evaluation of benefits. In the Methodology, CEA is most applicable for the Exposure Assessment.

Although CEA does not require a monetary estimate of the mitigation option benefits, it does require a quantitative estimate of them. Examples could include "area at risk," "population at risk," or other assets of interest at risk. The quantitative metric employed must be the same metric as used in the exposure assessment without and with the mitigation option. As with the CBA, in a CEA all costs and benefits should be evaluated over a common period of analysis. Streams of monetary costs over the period of analysis are converted to their present value using a common discount rate for comparison in CBA. Non-monetary benefit streams are not discounted in a CEA.

It is recommended that the period of analysis for CEA under this program be set at a timeframe that is aligned with the project's lifespan. The period of analysis for each CEA will begin at the "base year" and extend out X years for analysis of streams of mitigation option benefits and costs. The base year should be set as the year construction is complete.

The recommended steps for conducting a CEA are as follows:

- Evaluate non-monetary risk reduction benefits over the period of analysis
- Evaluate life cycle monetary costs over the period of analysis
- Convert all cost streams to their PV using current program discount rate
- Compare costs and benefits
- Document qualitative assessment of mitigation option cost effectiveness
- Evaluate uncertainties
- Present information for decision making

Now let us see these steps in more detail:

1. Evaluate Non-Monetary Risk Reduction Benefits

In some cases, it is not practical to quantify the benefits of a mitigation option in monetary terms. In such cases, the benefits can be presented in a quantified manner for comparison to costs. Non-monetary quantitative measures of risk reduction can be based on the exposure assessment and could include metrics such as reduction in area at risk, reduction in population at risk, or reduction in assets at risk. As described in BCA Step 2, the characterization of benefits is to be accomplished for both "without-mitigation" conditions and "with-mitigation" conditions. The difference between these two conditions represents the benefit of implementing the mitigation measure. In a CEA, it is important to describe the significance of the risk reduction to allow decision makers to make an informed choice regrading recommending a mitigation measure for inclusion in the DRMP.

2. Evaluate Life Cycle Monetary Costs

CEA Action 3 is the same as documented above for CBA Step 3.

3. Convert Cost Streams to Their Present Value

CEA Action 4 uses the same methods as described above for BCA Step 4 but is only applied to cost streams, as benefits are not quantified in monetary terms for the CEA procedure.

4. Compare Costs and Benefits

The analyst should tabulate and compare the costs and benefits of the mitigation option. Average cost per unit output should be tabulated for the option. If multiple mitigation options are under consideration, then the options can be ranked in order of average cost. Cost-effective options may be identified as the plan that produces each successive level of output at the least cost. Documentation of the significance of risk reduction developed in CEA Step 1 should be included.

5. Qualitative Assessment of Cost Effectiveness

Based on the results of CEA Step 4, the analyst will make a recommendation on whether the risk reduction associated with a mitigation option is justifiable to include in the DRMP based on its associated level of attainment of objectives, significance of the risk reduction, and costs.

6. Evaluate Uncertainties

CEA Step 7 is the same as documented above for BCA Step 7.

7. Present Information for Decision Making

Risk communication is a critical component of the CEA. Results should be presented in a narrative that should describe the planning context and explain key outputs of the analysis with a level of detail appropriate to the intended audience. Information in the CEA narrative should address the following:

1. Project Name and Location and Expected Project Timeline
2. Identified Disaster Hazards
3. Description of risk mitigation Option
4. Date of CEA
5. Base Year for Analysis
6. Period of Analysis
7. Discount Rate
8. Risk Quantification Without Mitigation Option
9. Residual Risk Quantification With Mitigation Option
10. Risk Reduction Benefits of the Mitigation Option
11. PV of Mitigation Option Costs
12. Qualitative Assessment of Cost Effectiveness of Mitigation Option
13. Uncertainty

6.1.6.2.3 Multi-Criteria Analysis (MCA)

There are several methodologies for creating an MCA for mitigation actions. With an MCA, stakeholders can define a standard set of evaluation criteria, assign scores, normalize scores, weight the criteria, and then rank the options.

This approach is a cost-effective method to screen and prioritize risk-mitigation options. MCA focuses on multiple success criteria that may be weighted and seeks decisions that maximize the greatest weighted response.

This approach also provides an opportunity to incorporate stakeholders and their views directly into the risk mitigation process, which promotes buy-in and ultimately, implementation, of the risk mitigation measures. However, this method is more subjective, and it may be difficult to get stakeholders to agree on criteria and weighting.

In the example from the Netherlands below (De Bruin, et al. 2009) a multi-criteria analysis was used to identify adaptation options to respond to climate change in connection to spatial planning. In this MCA 96 adaptation options were identified (including a wide range of policy measures and technological solutions), five evaluation criteria have been defined, scores were assigned from 1 to 5, and each criterion was weighted. The five criteria used were: (i) importance in terms of the expected gross benefits, (ii) the urgency reflecting the need to act sooner, (iii) the no-regret characteristics, i.e. if it is good to implement irrespective of climate change, (iv) the co-benefits to other sectors and (v) the effect on climate change mitigation, i.e. in reducing greenhouse-gas emissions. Thee scores obtained for each were then all added and weighed together to establish an overall ranking for each adaptation option. Table 6.18 shows the adaptation options with the highest scores that resulted from the ranking exercise. All of these have the same score of 4.9, and thus were selected as the prioritized options to implement. In contrast, the options with the lowest scores included “subsoil drainage of peatlands” with a score of 1.2 and “reclamation of part of southern North Sea” with a score of 1.4. specific maximum score and a weight, as shown in the table in the left side of Figure 6.28. Numerical scores for each metric category were developed rather than tangible values such as dollars. Costs were considered in terms of NPV and included land acquisition, construction, design, management, operation and maintenance costs and applied the anticipated project life. Benefits were divided into three: benefits of flood reduction, benefits on water quality and benefits on ecosystem restoration. The flood reduction benefits were considered in terms of avoided losses obtained via a proxy. The water quality benefits were considered in terms of reduction in total suspended solids and nitrogen as a result of the project. The ecosystem benefits were considered in terms of the amount of area where projects propose new or improved habitat. For details on how these dimensions were quantified, see GOSR (2017b).

The table on the right side of Figure 6.28 (GOSR, 2017) shows the results of the scoring exercise using these socres and weights. This table is sorted in descending order to show the options with the highest scores first, which represent the prioritized options.

Figure 6.28. LWTB Prioritization Framework, Incorporating MCA and BCA

costs **benefits** **vulnerability**

synergies **social resiliency**

Category	Metric	Category Weight	Maximum Score
	Total Costs	100%	25
Total Costs		**100%**	**25**
	Flood Reduction Water Quality Ecosystem/Habitat	45% 30% 25%	15.75 10.50 8.75
Total Benefits		**100%**	**35**
	Health and Safety Reduced Flooding Risk Future Adaptability	40% 40% 20%	6 6 3
Total Risk and Vulnerability		**100%**	**15**
	Program Synergies Municipal Dependencies Critical Infrastructure Leveraged Funds	30% 30% 20% 20%	3 3 2 2
Total Synergies		**100%**	**10**
	Improved Quality of Life Cultural Heritage Preservation Education Opportunities	33% 33% 33%	5 5 5
Total Social Resiliency		**100%**	**15**
MAXIMUM PRIORITIZATION SCORE			100

Each project was calculated based on five categories each category with varying metric weights.

13

PRIORITIZATION RANKING BREAKDOWN

ID	PROJECT NAME	Costs	Benefits	Risk & Vulner-ability	Syner-gies	Social Resi-lent	Total Project Rating
V	*Coastal Marsh Restoration*	0.0	32.4	8.2	3.3	6.6	50.5
B	*Horsebrook Drain West Branch Recharge Basin*	7.0	25.3	11.4	1.9	0.8	46.4
DD	*Hempstead High School Creek Restoration*	23.9	7.4	2.2	5.7	5.8	45.0
II	*Cooper Square*	19.8	14.7	2.3	6.1	0.0	42.9
M	*East Rockaway High School/Lister Park*	10.3	13.8	6.0	4.9	7.8	42.8
H	*Malverne High School*	18.0	11.3	2.1	4.8	6.2	42.4
F	*Malverne Green Streets*	12.1	19.6	3.8	5.3	0.4	41.2
A	*Hempstead Lake State Park*	0.0	13.6	11.3	5.3	10.7	40.9
L	*Smith Pond*	12.8	9.1	4.7	5.7	7.4	39.7
C	*Hempstead Housing Authority*	20.0	8.2	7.2	3.6	0.2	39.2
N	*Forest Avenue*	22.5	4.9	4.8	6.1	0.4	38.7
P	*East Boulevard and West Boulevard*	18.8	6.2	6.3	5.4	2.0	38.7
E	*Southwest Village of Hempstead Suspended Pavement Green Streets*	5.0	22.1	6.1	5.3	0.0	38.5
X	*S Centre Avenue Bioretention Green Street*	24.5	1.6	2.7	6.1	3.5	38.4
EE	*Covert Street*	24.5	0.6	5.7	6.8	0.0	37.6
KK	*Southern State Parkway Ramp*	23.8	3.9	3.4	6.1	0.0	37.2
HH	*Nichols Court*	24.0	1.3	2.5	6.1	0.0	37.2
J	*Lynbrook Recharge Basin*	24.7	4.2	3.9	3.6	0.0	37.2
D	*Northeast Village of Hempstead*	4.1	21.9	6.8	2.5	0.0	35.3

6.1.6.2.4 Optimization methods

The BC and Multi-Criteria analyses detailed above can further be used to analyze cases where there are multiple mitigation options, and these can be combined in different ways to form packages of measures. Instead of evaluating each measure individually and selecting one or a couple, it may be necessary to evaluate several combinations of them and then rank and find the top "package" options that combine individual measures. Optimization-like analytical methods are used for this.

One of these approaches involves using genetic algorithms to perform an optimization exercise of a multitude of alternatives when the analysis of options includes innumerable combinations that cannot be analyzed individually. Cardona et al. (2017b) developed this approach to assess and rank the best alternatives to a flooding risk problem. A fully probabilistic risk assessment was applied to obtain the LEC, AAL and PML for a large portfolio of housing across 11 municipalities in Colombia and then various mitigation measures were proposed. However, the number of combinations of possible measures (including raising houses at different heights, building urban flood protections for different urban centers and building a levee) resulted in the order of thousands. Thus, this algorithm was used to assess, using BC ratios and other metrics, combinations of different groupings (or packages) of measures with different technical characteristics and applied to different sub-portfolios simultaneously.

In summary, a genetic algorithm uses the concept and process of natural selection and genetics to select the optimum solution to a problem through iterative "genetic" modifications to the options (see Arora, 2012). The approach used by Cardona et al. (2017b) consists of the following steps:

1. The entire set of possible solutions represents a population where each solution represents an individual of that population. Each individual has a genotype, which is the genetic composition of that solution and consist of multiple genes, which are specific configurations of that solution. This means that each individual represents a solution package composed of various individual measures or alternatives. In the first step, a population is randomly generated.

2. All the individuals are evaluated for their fitness, that is, they are evaluated for the criteria that is being optimized (e.g., BCR, maximum benefit, etc.). The individual with the best performance under the evaluation criteria (the fittest) is chosen as the "champion."

3. The champion then undergoes a process of crossover and mutation with the rest of the population to create a new generation of individuals that now have different configurations of measures.

4. The individuals of the new generation are again evaluated for their fitness and a champion is selected. This process is repeated for many generations until the last champion meets a specified threshold for optimization or a defined number of generations is fulfilled.

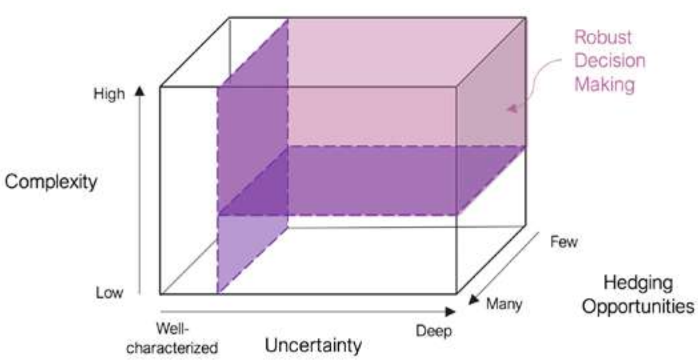
This approach is best suited for cases where there are innumerable configurations of possible mitigation measures.

6.1.6.2.5 Robust Decision Making or Decision Making Under Deep Uncertainty

Evaluation of uncertainty stemming from all parts of a risk model, including from a changing climate, is the objective of performing a probabilistic risk assessment (described above in Risk Assessment Approaches). The methods described there use explicit numerical quantification of those uncertainties, which leads to the results having these uncertainties already considered and calculated. These results are then used to propose, evaluate, and select risk-reduction measures or project alternatives. The tools and methods described above in this section for the evaluation of risk reduction measures can be directly used in conjunction with those risk assessment methods. However, there is another approach which has the same objective but goes about it in a slightly different manner: Robust Decision Making (RDM) or Decision Making Under Deep Uncertainty (DMDU).

This RDM approach represents another option to evaluate risk reduction measures and project alternatives. This approach has had different names over the years, including Exploratory Analysis (1993), RDM (2003), Decision Scaling (2011), Multi-objective Robust Decision Making (MORDM) (2013), but all of them address deep uncertainty in decision making. Deep uncertainty stems from large or existential scientific uncertainties. It exists when there is no agreement on the likelihood of alternative futures or how actions are related to consequences, and it is typically not well bounded Groves, 2017). Figure 6.29 shows a visual representation of when it is appropriate to use RDM.

Figure 6.29. Indicative Representation of When to use RDM



Source: Groves (2017).

RDM (Fischbach et al., 2015; Groves and Lempert, 2007) acknowledges that there may be no consensus to be achieved on future conditions under conditions of deep uncertainty. In the risk calculation, instead of an "agreement on assumptions," RDM pursues an "agreement on potential actions." That is, the RDM approach refrains from making explicit predictions about which future will occur in the risk calculation and instead focuses on evaluating potential feasible actions for associated risks and benefits. The focus of such an approach is addressing uncertainty not by an explicit numerical quantification but by selecting robust actions that will maximize benefits across the likely range of potential future conditions. Bottom-up decision models that start with a range of strategic options and evaluate the success of each to the range of possible futures are more likely to identify solutions that are robust and achieve consensus among otherwise skeptical stakeholders. Visit the Society for Decision Making Under Deep Uncertainty at www.deepuncertainty.org for more details.

This RDM approach was developed by the RAND Corporation and involves:

1. Identifying uncertain factors (**X**), policy levers (**L**), system model relationships (**R**), and performance metrics (**M**) or combined, the **XLRM Factors** (Fischbach et al., 2015): The performance measure (M) involves identifying the objectives and metrics of the decision problem (e.g., the goal, what success means, how success is measured). The policy lever (L) involves identifying policy options that could meet the policy objectives (the range of possible actions). Identifying uncertainties (X) involves identifying factors whose dimensions are deeply uncertain and could affect the success of the proposed options. The system model relationships (R) involves identifying how the system operates so one can construct a simulation model.

2. Evaluating the plan options under future conditions (Fischbach et al., 2015): Typically, for full RDM implementation, this step consists of advanced mechanistic or process models that run iterative combinations of the range of uncertain input factors and management options. The output is used

to interpret success or failure relative to the performance measures.

3. Evaluating the vulnerability of actions (Fischbach et al. 2015): The goal of this action is to identify vulnerable conditions, or scenarios under which a particular option fails. As the number of uncertain factors increases and the matrix of possible combinations of these factors becomes hyperdimensional or non-linear, identifying those that influence the failure of certain options becomes increasingly difficult. Advanced RDM efforts use multivariate exploratory statistical modeling (e.g., patient rule induction method (PRIM)) to overcome this. The result of this action is often reduced predictor space over which management options succeed and fail.

4. Considering new or hybrid strategies: After the third action, robust strategies may be apparent. However, it may happen that no strategy is sufficiently robust and, in action 4, new or hybrid management options or strategies are developed and run through the process again (Fischbach et al., 2015). The process itself may help inform what characteristics of novel alternative options or strategies one needs to improve the chances of identifying robust options.

After those actions are completed, one has hopefully identified robust decisions that perform the best under the greatest range of future uncertainties. Robust decisions may not be optimal under any one condition but are generally successful across the greatest number of uncertain futures. In this way, RDM shares much with low regret/no regret approaches.

This is an important part of defining goals and success during the first phase of RDM exercises. RDM generally seeks to avoid a singular target that may require negotiation among stakeholders, but rather seeks to define the breadth of success criteria against which solutions are matched. For adaptive or hybrid RDM approaches being considered by local water resource managers unencumbered by diverse stakeholders, however, alternative success definition methods may be useful to consider and may be easier to evaluate. For example, successful scenarios could also be defined using MiniMax (minimizing the maximum regret, where regret is the difference between the optimal outcome and any particular decision model outcome) or MaxiMin (maximizing the minimum regret). Refer to Groves and Lempert (2007) and Fischbach et al. (2015) for more details.

The IDB has already started working with RDM methodologies, particularly with the transportation sector, using what is now more commonly known as a Blue Sport Analysis. Please refer to the DMDU Guidebook for Transportation Planning Under a Changing Climate (Lempert et al., n.d.) for more details on this approach. This Guidebook was prepared for and funded by the IDB and is intended to help IDB team leaders, technical experts, planning and executing agencies, and consultants in conducting an analysis of decision making under deep uncertainty, which is one approach to the thinking process of evaluating and making decisions under a risk management context. It presents the methodological steps that are necessary for the implementation of Decision Making Under Deep Uncertainty (DMDU) methodologies. Specifically, it introduces and provides guidance on applying methods for DMDU to transportation planning and reviews several such methods, including scenario planning, adaptive pathways, and robust decision making (RDM).

6.1.6.3 Disaster and Climate Change Risk Management Plan

The DRMP should document the mitigation measures (encompassing both structural and non-structural options, information from Appendix G may be used for consideration), assessment and findings, and the ultimate recommendations, including the prioritization of the mitigation measures. It is important to document the justification for each measure carried forward in terms of (i) effectiveness at achieving risk reduction objectives, (ii) economic efficiency (positive net benefits from a BCA or determination of cost effectiveness from a CEA or MCA), (iii) qualitative account of the significance of the risk reduction benefit, and (iv) discussion of residual risk. In the development of the DRMP, it is also possible to engage in stakeholder outreach and engagement activities to identify and prioritize options. A general outline of a DRMP is shown next.

1. **Introduction**
2. **Disaster and Climate Change Risk Assessment Summary**
    a. Estimated Risk (per priority hazard)
        i. Baseline Risk without the Project (especially for surrounding communities)
        ii.Risk with the Project (risk to infrastructure and operations and risk, creation or exacerbation, to surrounding environment and communities)
3. **Identification of Risk Management Options**
4. **Assessment and Prioritization of Risk Management Options**
5. **Management Plan**
    b. Measures targeted at the Project Design (related to project viability)
        i. Structural Measures
        ii. Non-structural Measures
    c. Measures targeted at Project Construction and Operation
        i. During Construction
            1. Short-term Action Plan
                a. For the project
                b. For third parties (surrounding communities)
            2. Long-term Action Plan
                a. For the project
                b. For third parties (surrounding communities)
        ii. During Operation
            1. Short-term Action Plan
                a. For the project
                b. For third parties (surrounding communities)
            2. Long-term Action Plan
                a. For the project
                b. For third parties (surrounding communities)

7. Concluding Remarks

7. Concluding Remarks

Disaster and climate change risk assessment at the project level is a relatively new topic, but the science and technical knowledge are growing. Countries in the region have identified the need for clear methodologies and resources to undertake risk studies to better understand and address vulnerability and resilience while accounting for uncertain variables as part of project decision-making processes. In most countries, projects should undergo a risk screening to comply with national public investment system standards. Practical experience with detailed disaster and climate change risk assessments during project preparation is limited due to funding and expertise limitations and a lack of understanding of needs and benefits. There is a need to support these processes and to increase capacity building on risk assessment at the executing agency level.[31] Acting before disaster strikes can actually be more economical (Box 7.1).

Box 7.1. Resilience and Disaster Risk Reduction Payoff

According to Resource for the Future (RFF) (Kousky, 2017), in the United States, most federal funding for flood risk reduction is appropriated after disasters strike. This is also the case in most Latin American countries. There are several downsides to this. First, funds are spent during emergency and reconstruction phases in the flooded areas, but these are not necessarily the most high-risk areas, or where benefits can be provided to the most people and where most of the assistance is needed. Also, there is less time to spend funds with care. Allocating a greater share to pre-flood programs could improve the effectiveness of spending (RFF, 2017), because with ex-ante activities there is more time for careful planning and program development. Also, it is more efficient, since resources can be targeted in the riskiest areas and to the most cost-effective projects.

Keeping in mind the fact that the LAC region's disaster losses have increased from approximately US$13.5 billion to US$59 billion from 1960 to 2015 (EM-DAT, Bureau of Labor Statistics, and IDB personnel calculations), that according to the report Natural Disaster Hotspots: A Global Risk Analysis (World Bank, 2005), 7 out of the 15 counties most exposed to multiple hazards are in LAC, and that climate change adds another layer of risk, the circumstances of the region become critical.[32] However, it has been shown that resilience and disaster risk prevention yield benefits of about four to seven times the cost in terms of avoided and reduced losses (UNDRR, 2011; Kull et al., 2013; Micheler, 2015; MMC, 2005; Moench et al., 2007). Consequently, in light of this context it is clear that financing ex-ante resilience measures is key. While risk assessments might be initially perceived as requiring additional resources during project preparation, in the end they will pay off by better informing risk reduction efforts and thus estimations of the funding required for ex-post emergency response, and by helping prioritize measures based on relevance and availability of resources.

31 Efforts at the Bank to start addressing this issue include two training courses on disaster risk assessment (including the effects of climate change) held in 2016 and 2017. The Small Private Online Course (SPOC) and the Massive Open Online Course (MOOC) currently being developed by KIC, RND, CCS and ESG on disaster risk assessment (including the effects of climate change) for public investment systems will further strengthen capacity in the LAC region.

32 Numbers from previous disasters in LAC include: Hurricane Mitch in Central America (Oct. 1998) resulted in US$5 billion in losses and 10,000 deaths; the Venezuela landslide (Dec. 1999) resulted in US$1.79 billion in losses and 30,000 deaths; the Haiti earthquake (Jan. 2010) resulted in US$7.8 billion in losses and over 200.000 deaths; the Chile earthquake (Feb. 2010) resulted in US$30 billion in losses; the Colombia floods (Nov.-Dec. 2010) resulted in US$5.0 billion in losses and 389 deaths; the Buenos Aires floods (Apr. 2013) resulted in US$100 million in losses and 100 deaths; Hurricane Matthew in The Bahamas (Oct. 2016) resulted in US$600 million in losses.

The development of this Methodology arises from a need to consolidate a conceptual framework for the management of disaster and climate change risk that is applicable to all projects. While this Methodology initially focused on projects with infrastructure components, it will eventually include other relevant projects. An **experiential learning approach** has been critical to arrive at the current Methodology, which will improve as progress is made in its application and new lessons are learned. To date, some of the most important lessons learned include: (a) the need for the methodology to be sequential and gradual, but at the same time aligned and in compliance with the existing policy, with projects going through a qualitative analysis before a more complex quantitative one; (b) the need for time flexibility in the development of the DRA, that is, the point in the project cycle when it is most appropriate to perform a DRA to derive more appropriate and specific recommendations will depend on the nature of the project; (c) that it is highly beneficial to have a methodology that is rooted in the OP-704 Policy, but which can also be applied through regular project mainstreaming as a good practice to achieve resilience; (d) the relevant role that supervision plays in identifying and evaluating disaster and climate change risk management by executing agencies (maintenance is key, see Box 33); (e) the importance of involving project counterparts to ensure that DRAs can influence project design, construction and operation, as applicable, and that risk reduction measures are maintained to ensure sustainability; (f) the need to acknowledge that applied experience in conducting DRAs at the project level is growing but is still not standardized, even when considering leading engineering firms, and thus the importance of working on methodological documents, piloting, and capacity building.

The application of this Methodology is a key investment. Together with the Bank's Sustainable Infrastructure Framework and The Bahamas Resolution Commitments, the Disaster Risk Management Policy provides an opportunity for the Bank and its client countries to reduce risks and add value to projects. In a context of global change, this can make a difference for vulnerable countries to successfully achieve sustainable development.

Box 7.2. Maintenance is Critical to Improve Disaster and Climate Change Risk Management

A critical action to reduce risks is to invest in operation and maintenance tasks to ensure a project reaches its life-span and development objectives as set forth in the project design, and to ensure project resilience to long term changes in climate conditions. Infrastructure cannot be resilient if it is poorly maintained. As already discussed, disasters result from a combination of hazards, exposure and vulnerability, and adequate maintenance directly helps reduce vulnerability. A report by Gallego-Lopez and DFID makes the case for increasing the resources required to pay for adequate maintenance, and to adapt maintenance and operation schemes to new climate patterns. They also make a strong case for the importance of having a certain degree of redundancy in projects and mechanisms to quickly recover after a shock. Said report recommends bridging the gap from modelling to engineering designs by, for example, identifying sections of a road that are most at risk from flooding using risk models with different flood severities and road alternatives. In many countries, lack of maintenance and poor drainage are already critical issues affecting the road network.

The IDB is addressing this issue through a series of Blue Spot Analyses,[33] and by conducting risk assessments in relevant projects. Note that this document also points out that climate screening mechanisms are necessary, but not sufficient, because they follow investment decisions, rather than precede and set the context for taking them (Gallego-Lopez, 2016).

33 The Blue Spots model is a method to identify flood-sensitive areas, specifically in road networks. A blue spot is defined as a stretch of road where the likelihood of flooding is relatively high and where its consequences are significant. The Blue Spot methodology is applicable to any country if the required data are available.

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Appendix A: Acronyms and Abbreviations

AAL	Average annualized loss
AAR	Artificial aquifer recharge
AASHTO	American Association of State Highway and Transportation Officials
ANN	Artificial neural network
ASCE	American Society of Civil Engineers
B	Holland pressure profile parameter (hurricane track simulation model)
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
BMP	Best management practice
BPJ	Best professional judgement
C	Translation speed (hurricane track simulation model)
CAPRA	Central America Probabilistic Risk Assessment
CEA	Cost-effectiveness analysis
cm	Centimeter
DEM	Digital elevation model
DEM	Development Effectiveness Matrix
DLP	Draft loan proposal
dmin	Distance of closest approach (hurricane track simulation model)
Dp	Difference in pressure (hurricane track simulation model)
DRMP	Disaster risk management plan
EA	Environmental assessment
EIA	Environmental impact assessment
EP	Exceedance probability
ERM	Eligibility review meeting

ERR	Economic rate of return
ESG	Environmental Safeguards Unit
ESMP	Environmental and social management plan
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GCM	Global climate model
GI	Green infrastructure
GIS	Geographic information system
ha	Hectare
Hazmat	Hazardous material
HDPE	High-density polyethylene
HR	Human resources
hr	hour
I&C	Instrumentation and control
IBC	International Building Code
IDB	Inter-American Development Bank
IFC	International Finance Corporation
IML	Intensity measure level
IMR	Intensity-measure relationship
IMT	Intensity measure type
IVM	Information value model
km	Kilometer
L	Policy levers (RDM process)
L	Liter
LAC	Latin America and the Caribbean
LID	Low-impact development
LWTB	Living with the Bay
M	Performance metrics (RDM process)

m	Meter
m^2	Square meters
MEA	Modeled event analysis
MCA	Multi-criteria analysis
mg	Milligram
MGD	Million gallons per day
M&E	Monitoring and evaluation
mm	Millimeter
OPC	Operations Policy Committee
PA	Probabilistic analysis
PCR	Project completion report
PDSI	Palmer Drought Severity Index
PEA	Past event analysis
PGA	Peak ground acceleration
PGV	Peak ground velocity
PMR	Progress monitoring report
POD	Proposal for Operations Development
PP	Preparation phase
PRIM	Patient Rule Induction Method
PV	Present value
PVC	Polyvinyl chloride
Q	Heading (hurricane track simulation model)
QA	Qualitative analysis
Qcr	Critical rainfall threshold (landslide model)
QRR	Quality and risk review
R	System model relationships (RDM process)
r	Discount rate (benefit–cost analysis equation)
RDM	Robust Decision Making

Rmax	Radius to maximum winds (hurricane track simulation model)
S	Future sum (benefit–cost analysis equation)
SA	Susceptibility analysis
SEA	Strategic Environmental Assessment
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standard Precipitation Index
STAPLEE	Social, technical, administrative, political, legal, economic, and environmental criteria
t	Year of the period of analysis (benefit–cost analysis equation)
TOR	Terms of reference
TSS	Total suspended solids
USGS	United States Geological Survey
WHO	World Health Organization
X	Uncertain factors (RDM process)

Appendix B: Definitions

The DECIDIR guidance draws upon key concepts from both the climate change and the disaster risk reduction communities of practice. As each community has developed distinct definitions related to risk assessment and risk management, it is prudent to define key concepts and specify the terminology that is used in the guidance.

Adaptive capacity: The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (NRC, 2010).

Climate variability: Variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events (IPCC, 2007).

Climate change: The United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also climate change commitment, detection, and attribution.

Climate change risk management as used here as interchangeable with the definition of adaptation, which is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects (IPCC, 2014).

Disaster: The occurrence of an extreme hazard event that impacts vulnerable communities, causing substantial damage, disruption, and possible casualties, and leaving the affected communities unable to function normally without outside assistance (Benson and Twigg, 2007).

Disaster preparedness: Activities and measures taken in advance to ensure an effective response to the impact of hazards, including the issuance of timely and effective early warnings and the temporary evacuation of people and property from threatened locations, and contingency planning (IDB, 2008).

Disaster risk management: The systematic process that integrates risk identification, prevention, mitigation, and transfer, as well as disaster preparedness, emergency response, and rehabilitation/reconstruction to lessen the impacts of hazards (IDB, 2008).

Disaster risk reduction: The systematic development and application of policies, strategies, and practices to minimize vulnerabilities, hazards, and the unfolding of disaster impacts throughout a society, in the broad context of sustainable development (IDB, 2008).

Exposure: The presence of people, livelihoods, environmental services, resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by climate change effects (IPCC, 2012).

Financial protection: Ex ante activities to prepare financial mechanisms or instruments for risk retention and transfer to have ex post access to timely economic resources, which improves the response capacity in the event of disaster.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, or environmental resources (IPCC, 2014). This definition recognizes that hazards exist under current conditions and may be exacerbated under future climatic conditions.

Hazard mitigation: Reducing existing risk through structural and non-structural measures undertaken to limit the adverse impact of natural hazards, environmental degradation, and technological hazards. The word hazard is included in front of mitigation to differentiate it from mitigation defined in the climate change context as "a human intervention to reduce the sources or enhance the sinks of greenhouse gases" (IPCC, 2014).

Resiliency: The capability of a system (such as a community) to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimal damage to social well-being, the economy, and the environment (NRC, 2010). This concept recognizes the complementarity of climate change adaptation and disaster risk reduction.

Rehabilitation: Provisional repairs of damaged infrastructure, social services or productive capacity to facilitate the normalization of economic activities (IDB, 2008).

Reconstruction: Construction of new facilities to replace those that were destroyed or damaged beyond repair by a disaster, to standards that avoid the rebuilding or increasing of vulnerability (IDB, 2008).

Risk: A combination of the magnitude of the potential consequence(s) of hazard and the likelihood that the consequence(s) will occur (NRC, 2010).

Risk reduction: The systematic development and application of policies, strategies, and practices to minimize vulnerabilities, hazards, and the unfolding of disaster impacts throughout a society, in the broad context of sustainable development. It includes mitigation and prevention. Mitigation (reduce existing risk) refers to structural and non-structural measures undertaken to limit the adverse impact of natural hazards, environmental degradation, and technological hazards. Prevention (prevent new conditions of risk) refers to activities to avoid the adverse impact of hazards and means to minimize the impacts of related disasters.

Risk transfer: The process of formally or informally shifting the financial consequences of particular risks from one party to another. Insurance is a well-known form of risk transfer, where coverage of a risk is obtained from an insurer in exchange for ongoing premiums paid to the insurer.

Sensitivity: The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Slow-onset versus rapid-onset hazard: Slow-onset hazards are those that occur over months or years (such as sea-level rise or drought), and rapid-onset hazards occur over shorter time intervals, such as hurricanes, floods, or storm surges.

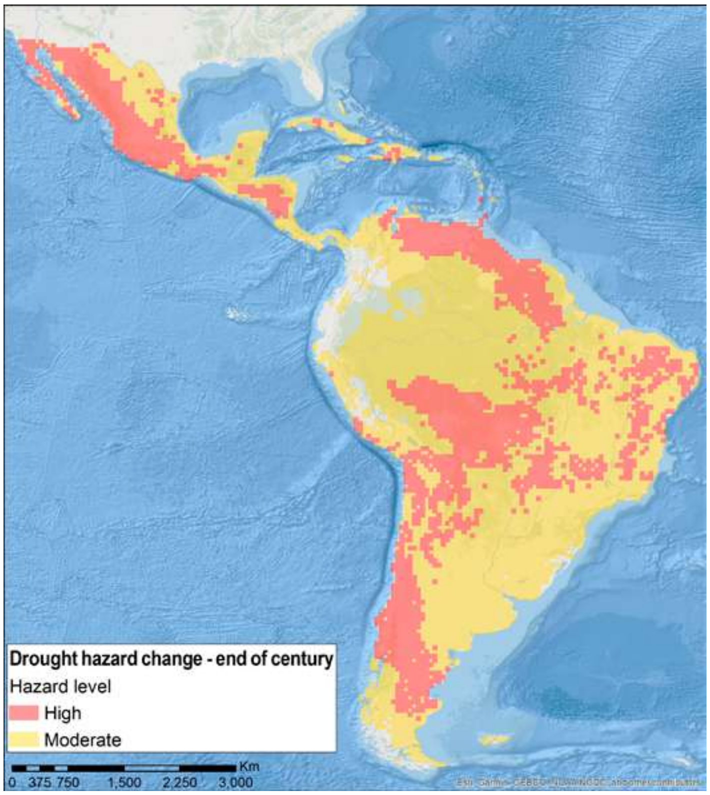
Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (NRC, 2010).

Weather: The atmospheric conditions at a particular place in terms of air temperature, pressure, humidity, wind speed, and rainfall. Weather includes current atmospheric conditions or those that are likely to happen in the very near future.

Appendix C: Screening Hazard Maps

Hazard Layers

Map AC.1: Drought Hazard



This layer shows drought hazard. The model behind this map does not consider variations due to climate change (that is, it assumes there will be no significant change over time, in the way the hazard has presented itself historically).

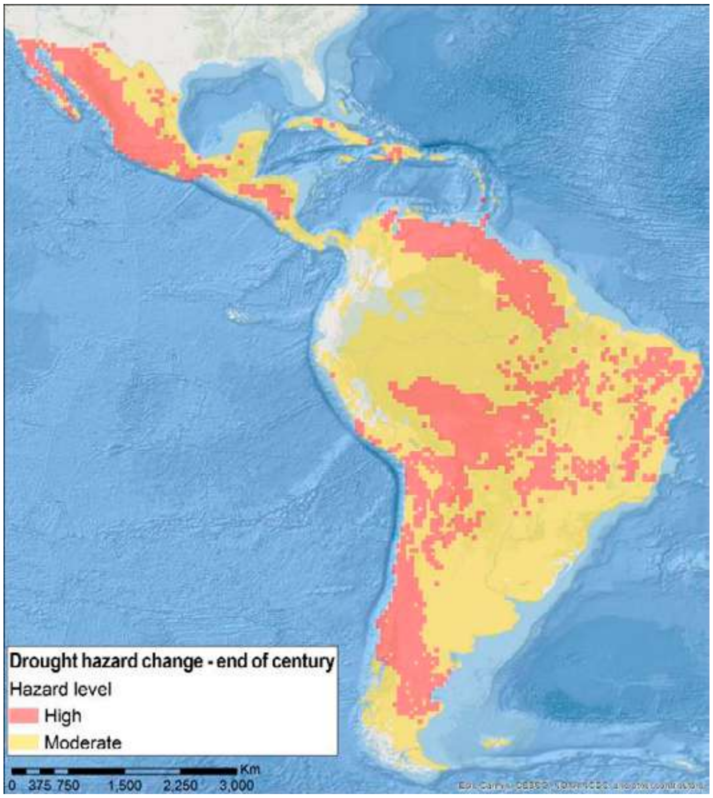
This layer shows the map for drought hazard. The index depicted in this map is the number of years within a window of 20 years from 1980 to 2001 where at least one drought event occurred). Areas with one year or less with drought events are considered "low," areas with two or three years with drought events are considered "moderate," and areas with more than three years with drought events are considered "high."

This layer was created from a polygonal dataset (derived from 55-km gridded global data), which allows users to identify areas that may be subject to droughts based on historical data (1980–2001). It is based on two sources: (i) a global monthly gridded precipitation dataset obtained from the Climatic Research Unit (University of East Anglia), and (ii) a GIS modeling of the global Standardized Precipitation Index based on Brad Lyon (IRI, Columbia University) methodology. Drought events are defined as areas where monthly precipitation is lower than 50 percent of the median value calculated for the period 1961–1990 during at least three consecutive months. This product was designed by UNEP/GRID-Europe for the Project of Risk Evaluation, Vulnerability, Information, and Early Warning (PreView). This layer must be read together with the future drought hazard layer considering climate change to evaluate, first, the hazard levels without climate change and, second, the magnitude of the expected change (in this case, increase) of drought hazard for the end of the century once climate change is included.

Data source: UNEP (United Nations Environment Programme) and UNISDR (United Nations International Strategy for Disaster Reduction). 2015. Global Risk Data Platform. Drought – Events [Shapefile geospatial data dr_events_shapefile]. Drought Hazard. Created by the Inter-American Development Bank (IDB) by processing the original dataset. Available at https://preview.grid.unep.ch/index.php?preview=data&events=droughts&evcat=1&lang=eng

Limitations: The data employed in the creation of this metric is historical and therefore not predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by UNEP may not capture localized conditions of future drought events and therefore should not be used to represent areas affected by future events. The data provided are meant to offer general trends in probability for this hazard, but only to guide more localized decision-making considerations.

Map AC.2: Drought Hazard: End of the Century (with climate change)



This layer shows the change in drought hazard by the end of the century. The model behind this map considers variations due to climate change.

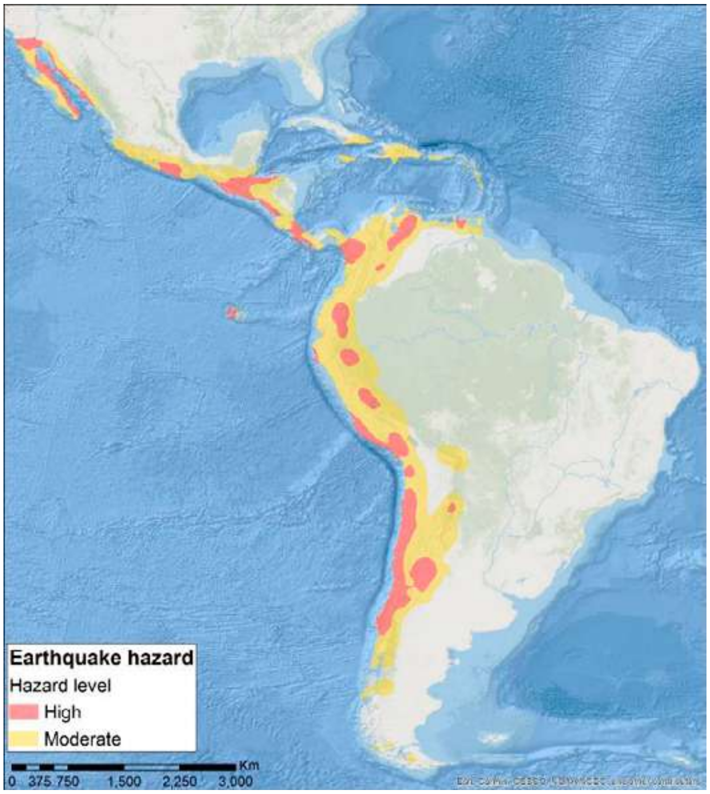
This layer shows the change in drought hazard by the end of the century, considering climate change (percentage change in the occurrence of days under drought for the period 2070-2099 relative to 1976-2005). Percentage changes between -100 percent and +25 percent are considered "low," percentage changes between +25 percent and +50 percent are considered "moderate," and percentage changes greater than +50 percent are considered "high."

This layer was created by estimating future change (positive, negative, or no change) in drought hazard using the methodology outlined by Prudhomme et al. (2014). Daily runoff data from 68 global impact models (GIMs) and 5 global climate models (GCMs) from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Fast Track data archive was used to estimate the occurrence of future droughts by comparing runoff from the future period (2070–2099) to the historic period (1976–2005). Each grid cell was assigned a drought index of 1 if runoff on a given day was less than a daily threshold (10th percentile - Q90 - of flows across a 30-day moving window), and 0 otherwise. For each grid cell, a measure of drought frequency was calculated as the fraction of days under drought. This layer must be read together with the stationary drought hazard layer (without considering climate change) to evaluate, first, the hazard levels without climate change and, second, the magnitude of the expected change (in this case, increase) in drought hazard for the end of the century once climate change is included.

Data source: ISIMIP. 2017. Fast Track data archive. Drought Hazard – Change for the End of the Century (with Climate Change). Created by the IDB by processing the original dataset. Retrieved from https://esg.pik-potsdam.de/search/isimip-ft/

Limitations: The data employed in the creation of this metric are from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by ISIMIP (~55-kilometer resolution) may not capture localized conditions of future drought impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard, but only to guide more localized decision-making considerations.

Map AC.3: Earthquake Hazard



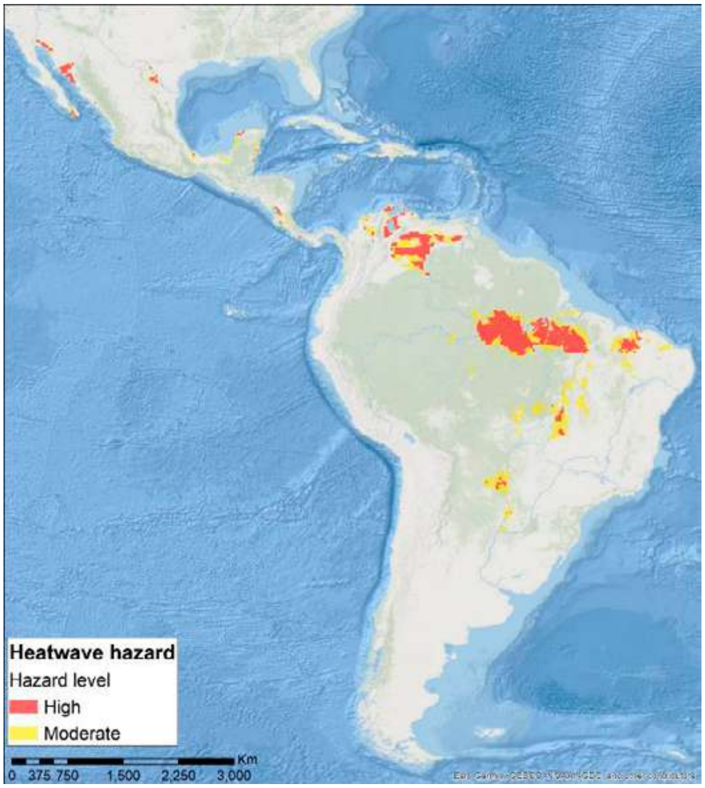
This layer shows the probabilistically integrated hazard map for peak ground acceleration, or PGA (maximum acceleration of the ground – in cm/s2 or gal), at rock level, that is, without considering the effect of local soils, for a return period of 475 years. PGA values below 90 cm/s2 are considered "low," PGA values between 90 cm/s2 and 177 cm/s2 (inclusive) are considered "moderate," and PGA values greater than 177 cm/s2 are considered "high."

This layer was created from an 8-km resolution gridded global dataset that would allow a user to identify areas that may be subject to ground motions. The data correspond to the output from the probabilistic seismic hazard model built for the UNISDR Global Assessment Report on Risk Reduction 2015 (GAR 15) global risk assessment. This hazard model applies historical data and predictive modeling efforts to obtain a set of stochastically simulated events that represents an exhaustive collection of all the events that could ever happen; this set not only respects past behaviors but also includes extreme events that have not necessarily occurred yet and that can still occur. This fully probabilistic seismic hazard model (developed by CIMNE and INGENIAR Ltd.) uses a set of tectonic provinces that were identified and characterized by means of a set of parameters that describe their future seismic activity based on historical records, together with relationships to obtain hazard intensities as a function of magnitude and distance. The hazard analysis was performed using the program CRISIS2014, a state-of-the-art tool for these kinds of tasks and widely known and acknowledged by experts in the field across the world; for more details about the probabilistic seismic hazard analysis, see Cardona et al. (2015).

Data source: UNISDR (United Nations International Strategy for Disaster Reduction). s.d.. GAR Atlas: Global Assessment Report on Disaster Risk Reduction - Risk Data Platform. Peak Ground Acceleration PGA 475 years [raster geospatial data Seismic_hazard_PGA_RT475years_g1537]. Earthquake Hazard. Created by the IDB by processing the original dataset. Retrieved from https://risk.preventionweb.net/capraviewer/download.jsp?tab=9&mapcenter=0,1123252.6982849&mapzoom=2

Limitations: While these data are not merely historical but involve predictive modeling, they still should not be considered predictive of where future hazards will be experienced or found. Furthermore, ground motion depends heavily, in some cases, on the specific soil conditions which can amplify ground motion significantly compared to the ground motion at rock level. Because this layer only depicts PGA at rock level, the acceleration values depicted should be treated with caution and local microzonation studies should be consulted to determine if amplifications could occur. Additionally, the scale of the data provided by UNEP may not capture localized conditions of future earthquake events and therefore should not be used to represent areas affected by future events. The data provided are meant to offer general trends in hazard, but only to guide more localized decision-making considerations.

Map AC.4: Heatwave Hazard



This layer shows heatwave hazard. The model behind this map does not consider variations due to climate change (that is, it assumes there will be no significant change, in time, in the way the hazard has presented itself historically).

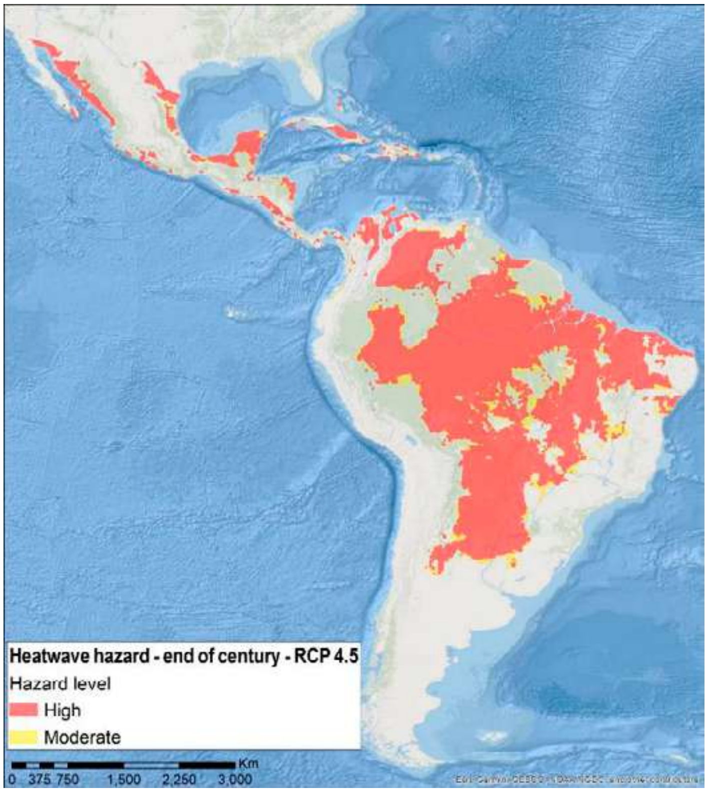
This layer shows the map for heatwave hazard (the index shown by this map is the average total degree days, or DD, of heatwave per year). DD values less than 79 are considered "low," DD values between 80 and 165 are considered "moderate," and DD values greater than 165 are considered "high."

This layer was created from three Global Climate Model (GCM) temperature datasets allowing users to identify areas that may be subject to heat waves based on historical time periods (1976–2005) using methods detailed by Meehl and Tebaldi (2004). Hindcasted temperature model data from three GCMs representing a low, median, and extreme range of future climate change were selected for development of Heat Wave using the referenced methods, where GFDL-ESM2G served as the 10th percentile, bcc-csm1-1 as the median, and CSIRO-MK3-6-0 as the 90th percentile for employment of the methodology offered by Meehl and Tebaldi (2004). The percentages are based on the number of days above extreme temperature (defined as the ith percentile of daily maximum temperature over the 30-year time period) within a particular region (i.e., grid cell). The duration and maximum temperature experienced during heat waves can help to indicate the severity of heat wave impacts. To incorporate these two factors, an index that combines duration and maximum temperature, called total degree days (DD) was used to assess heat wave hazard. Median values of dd across all three GCMs over the 30-year time period of the hindcast model scenario were used to create thresholds. Model data were chosen instead of measured, historical data providing a more appropriate comparison between this hazard layer output and the two heat wave layers considering climate change (these thresholds were also used for the two Heat Wave Hazard layers that consider climate change). This layer must be read together with the heatwave layers considering climate change to evaluate, first, the hazard levels without climate change and, second, how the hazard pattern changes for the end of the century once climate change under RCP 4.5 and RCP 8.5 is included (all three layers use the same data and modeling, so they are directly comparable).

Data source: NEX-GDDP (NASA Earth Exchange Global Daily Downscaled Projections). 2017. Data Access. Heatwave Hazard. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric are from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heatwave impacts and therefore should not be used to represent areas affected by future events. The data provided are meant to offer general trends in probability for this hazard, but only to guide more localized decision-making considerations.

Map AC.5: Heatwave Hazard: End of the Century under RCP 4.5 (with climate change)



This layer shows the heatwave hazard for the end of the century. The model behind this map considers variations due to climate change under Representative Concentration Pathway (RCP) 4.5.

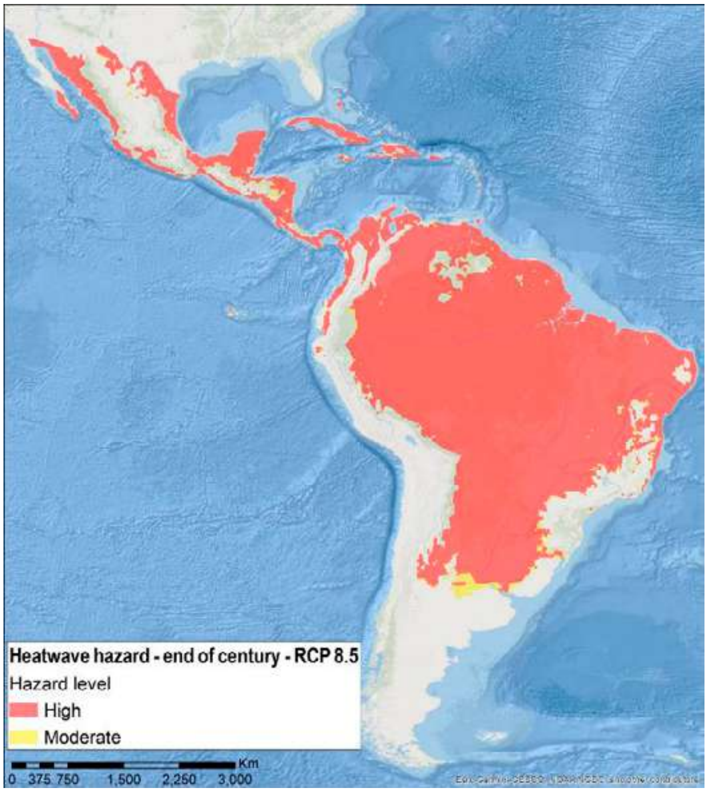
This layer shows the map for heatwave hazard for the end of the century, considering climate change under RCP 4.5 (the index shown by this map is the average total degree days, or DD, of heatwave per year). DD values less than 79 are considered low," DD values between 80 and 165 are considered "moderate," and DD values greater than 165 are considered "high."

This layer was created from three Global Climate Model (GCM) down-scaled temperature datasets allowing users to identify areas that may be subject to heat waves based on future time periods (2071-2100) using methods detailed by Meehl and Tebaldi (2004). Forecasted temperature model data under RCP 4.5 from three GCMs representing a low, median, and extreme range of future climate change (GFDL-ESM2G, bcc-csm1-1, CSIRO-Mk3-6-0, respectively) were selected, where GFDL-ESM2G served as the 10th percentile, bcc-csm1-1 as the median, and CSIRO-MK3-6-0 as the 90th percentile for employment of the methodology offered by Meehl and Tebaldi (2004). The percentages are based on the number of days above extreme temperature (defined as the ith percentile of daily maximum temperature over the 30-year time period) within a particular region (i.e., grid cell). The duration and maximum temperature experienced during heat waves can help to indicate the severity of heat wave impacts. To incorporate these two factors, an index that combines duration and maximum temperature, called total degree days (DD) was used to assess heatwave hazard. Model data was chosen instead of measured, historic data providing a more appropriate comparison between this hazard layer output, the reference hazard layer and the other Heat Wave Layers Considering Climate Change (these thresholds used are the same for all three layers). This layer must be read together with the stationary heatwave layer (without considering climate change) to evaluate, first, the hazard levels without climate change and, second, how these hazard levels change for the end of the century once climate change under RCP 4.5 is included (both layers use the same data and modeling, so they are directly comparable).

Data source: NEX-GDDP (NASA Earth Exchange Global Daily Downscaled Projections). 2017. Data Access. Heatwave Hazard – End of Century under RCP 4.5. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric are from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heat wave impacts and therefore should not be used to represent areas affected by future events. The data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.6: Heatwave Hazard: End of the Century under RCP 4.5 (with climate change)



This layer shows the heatwave hazard for the end of the century. The model behind this map considers variations due to climate change under Representative Concentration Pathway (RCP) 8.5.

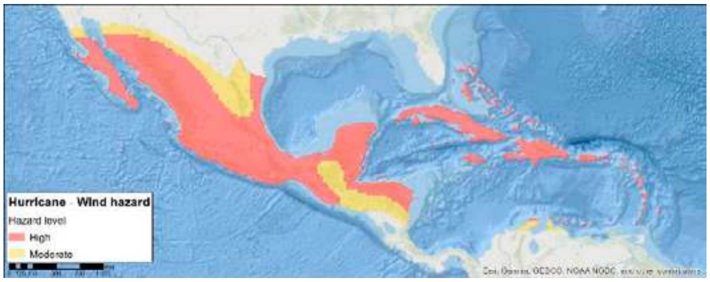
This layer shows the map for heatwave hazard for the end of the century, considering climate change under RCP 8.5 (the index shown by this map is the average total degree days, or DD, of heatwave per year). DD values less than 79 are considered "low," DD values between 80 and 165 are considered "moderate," and DD values greater than 165 are considered "high."

This layer was created from three Global Climate Model (GCM) down-scaled temperature datasets allowing users to identify areas that may be subject to heat waves based on future time periods (2071–2100) using methods detailed by Meehl and Tebaldi (2004). Forecasted temperature model data under RCP 8.5 from three GCMs representing a low, median, and extreme range of future climate change were selected, where GFDL-ESM2G served as the 10th percentile, bcc-csm1-1 as the median, and CSIRO-MK3-6-0 as the 90th percentile for employment of the methodology offered by Meehl and Tebaldi (2004). The percentages are based on the number of days above extreme temperature (defined as the ith percentile of daily maximum temperature over the 30-year time period) within a particular region (i.e., grid cell). The duration and maximum temperature experienced during heat waves can help to indicate the severity of heatwave impacts. To incorporate these two factors, an index that combines duration and maximum temperature, called total degree days (DD) was used to assess heatwave hazard. Model data was chosen instead of measured, historic data providing a more appropriate comparison between this hazard layer output, the reference hazard layer and the other heat wave layers considering climate change (these thresholds used are the same for all three layers). This layer must be read together with the stationary heatwave layer (without considering climate change) to evaluate, first, the hazard levels without climate change and, second, how these hazard levels change for the end of the century once climate change under RCP 8.5 is included (both layers use the same data and modeling, so they are directly comparable).

Data source: NEX-GDDP (NASA Earth Exchange Global Daily Downscaled Projections). 2017. Data Access. Heatwave Hazard – End of Century under RCP 8.5. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric is from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heatwave impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to provide general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.7: Hurricane Wind Hazard



This layer shows hurricane wind hazard. The model behind this map does not consider variations due to climate change (that is, it assumes there will be no significant change, in time, in the way the hazard has presented itself historically).

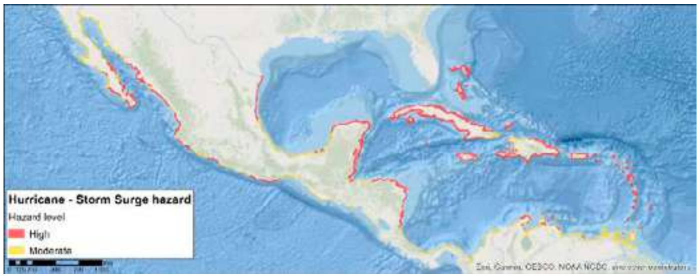
This layer shows the probabilistically integrated hazard map for wind speed (estimated 3-second sustained mean wind speed at 10 meters above water/ground surface – in km/h) for a return period of 500 years. Wind speed values below 185 km/h (including all other inland areas not already ranked as moderate or high) are considered "low," wind speed values between 185 km/h and 209 km/h (inclusive) are considered "moderate," and wind speed values greater than 209 km/h are considered "high."

This layer was created from a ~30-km resolution gridded global dataset allowing users to identify areas that may be subject to damaging winds from hurricanes. The data corresponds to the output from the probabilistic tropical cyclonic strong wind and storm surge hazard model built for the UNISDR Global Assessment Report on Risk Reduction 2015 (GAR 15) global risk assessment. This hazard model applies historical data and predictive modeling efforts to obtain a set of stochastically simulated events that represents an exhaustive collection of all the events that could ever happen; this set not only respects past behaviors but also includes extreme events that have not necessarily occurred yet and that can still occur. The model uses information from 2,594 historical tropical cyclones, besides data on topography, terrain roughness, and bathymetry. The historical tropical cyclones used in the cyclone wind and storm surge hazard model for the GAR 15 cover the six oceanic basins: Northeast Pacific, Northwest Pacific, South Pacific, North Indian, South Indian, and North Atlantic. In all cases, the data associated to each track were obtained from the IBTrACS database (Knapp et al., 2010). Topography data from NASA's Shuttle Radar Topography Mission (SRTM), which provides terrain elevation grids at a 90 meters resolution, delivered by quadrants over the world was used; additionally, to account for surface roughness, polygons of urban areas worldwide were obtained from the Socioeconomic Data and Applications Centre, SEDAC (CIESIN et al., 2011). A digital bathymetry model, with a spatial resolution of 30 arc-seconds, from the GEBCO_08 (General Bathymetric Chart of the Oceans) Grid Database of the British Oceanographic Data Centre (2009) was also used. The hazard modeling was performed using the software CAPRA Team Tropical Cyclones Hazard Modeler (Bernal, 2014); more information about the cyclone wind and storm surge hazard model can be found in Cardona et al., 2015.

Data source: UNISDR. s.d. GAR Atlas: Global Assessment Report on Disaster Risk Reduction - Risk Data Platform. Cyclone Wind 500 years return period [raster geospatial data Cyclonic wind_RT500years_g154]. Hurricane Wind Hazard. Created by the IDB by processing the original dataset. Retrieved from https://risk.preventionweb.net/capraviewer/download.jsp?tab=9&mapcenter=0,1123252.6982849&mapzoom=2

Limitations: While these data are not merely historical but involve predictive modeling, they still should not be considered predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by UNISDR may not capture localized effects of cyclone/hurricane storm effects and therefore should not be used to represent wind hazard expected from future events. Data provided are meant to provide general trends in hazard, only to guide more localized decision-making considerations.

Map AC.8: Hurricane Storm Surge Hazard



This layer shows storm surge hazard. The model behind this map does not consider variations due to climate change (that is, it assumes there will be no significant change, in time, in the way the hazard has presented itself historically).

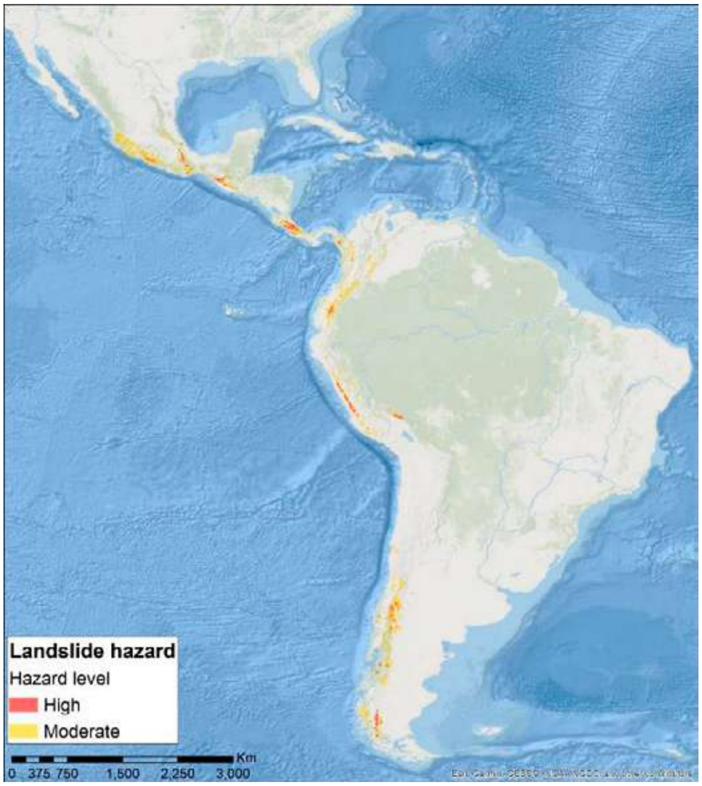
This layer shows the probabilistically integrated hazard map for storm surge run-up height (maximum vertical height onshore above mean sea level reached by the water – in meters) for a return period of 250 years. Run-up values below 0.1 meters (including all other inland areas not already ranked as moderate or high) are considered "low," run-up values between 0.1 meters and 2 meters (inclusive) are considered "moderate," and run-up values greater than 2 meters are considered "high." The areas identified as "moderate" or "high" were limited to areas within 5 km of existing tidally influenced (i.e., coastal) areas.

This layer was created from a global dataset of points that were buffered to create a zone of approximately 5 kilometers inland from coast lines—allowing users to identify areas that may be subject to storm surges from hurricanes. The point data correspond to the output from the probabilistic tropical cyclonic strong wind and storm surge hazard model built for the UNISDR Global Assessment Report on Risk Reduction 2015 (GAR 15) global risk assessment. This hazard model applies historical data and predictive modeling efforts to obtain a set of stochastically simulated events that represents an exhaustive collection of all the events that could ever happen; this set not only respects past behaviors but also includes extreme events that have not necessarily occurred yet and that can still occur. The model uses information from 2,594 historical tropical cyclones, besides data on topography, terrain roughness, and bathymetry. The historical tropical cyclones used in the cyclone wind and storm surge hazard model for the GAR 15 cover the six oceanic basins: Northeast Pacific, Northwest Pacific, South Pacific, North Indian, South Indian, and North Atlantic. In all cases, the data associated with each track were obtained from the IBTrACS database (Knapp et al., 2010). Topography data from NASA's Shuttle Radar Topography Mission (SRTM), which provide terrain elevation grids at a 90 meters resolution, delivered by quadrants over the world were used; additionally, to account for surface roughness, polygons of urban areas worldwide were obtained from the Socioeconomic Data and Applications Center, SEDAC (CIESIN et al., 2011). A digital bathymetry model, with a spatial resolution of 30 arc-seconds, from the GEBCO_08 (General Bathymetric Chart of the Oceans) Grid Database of the British Oceanographic Data Centre (2009) was also used. The hazard modeling was performed using the CAPRA Team Tropical Cyclones Hazard Modeler software (Bernal, 2014); more information about the cyclone wind and storm surge hazard model can be found in Cardona et al., 2015.

Data source: UNISDR (United Nations International Strategy for Disaster Reduction). s.d.. Global Risk Data Platform. Storm Surge Hazard 250 years [Shapefile geospatial data storm_surge_hazard_shapefile]. Hurricane Storm Surge Hazard. Created by the IDB by processing the original dataset. Retrieved from https://preview.grid.unep.ch/index.php?preview=data&events=gar2015&evcat=37&metaid=179&lang=eng

Limitations: While these data are not merely historical but involve predictive modeling, they still should not be considered predictive of where future hazards will surely be experienced or found. Additionally, the scale of the data provided by UNISDR may not capture localized effects of cyclone/hurricane storm surges and therefore should not be used to represent areas of inundation expected from future events. Data provided are meant to offer general trends in hazard, only to guide more localized decision-making considerations.

Map AC.9: Landslide Hazard



This layer shows landslide hazard. The model behind this map does not consider variations due to climate change (that is, it assumes there will be no significant change, in time, in the way the hazard has presented itself historically).

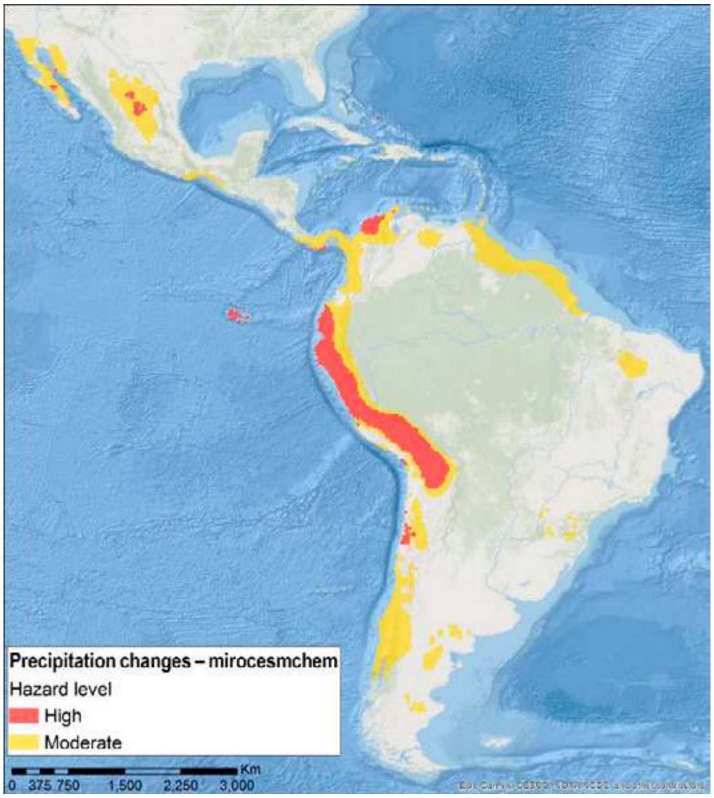
This layer shows the map for landslides hazard (the index shown by this map is the expected annual probability and percentage of pixel of occurrence of a potentially destructive event, multiplied by 1,000,000). Index values below 50 are considered “low,” values between 50 and 1,000 (inclusive) are considered “moderate,” and values above 1,000 are considered “high.”

This layer was created from three global datasets allowing users to identify areas that may be subject to landslide events. The data corresponds to the output from the landslide hazard assessment done for the UNISDR Global Assessment Report on Risk Reduction 2009 (GAR 09) global risk assessment. It was created using two UNEP 1-km resolution gridded datasets representing annual probability of landslides triggered by earthquakes or precipitation. They depend on the combination of trigger and susceptibility defined by six parameters: slope, lithology, soil moisture, veg. cover, precipitation, and seismic conditions. The third dataset was used to identify high-sloped areas (>10 percent) derived from a 30-m DEM produced by NASA’s SRTM that was then used to downscale both 1-km gridded GAR 09 datasets for more accurate landslide hazard mapping.

Data source: UNEP (United Nations Environment Programme) and UNISDR (United Nations International Strategy for Disaster Reduction). 2015. Global Risk Data Platform. Landslides – Frequency (triggered by Earthquakes and triggered by Precipitations) [raster geospatial data ls_eq_tiff and ls_pr_tiff]. Landslide Hazard. Created by the IDB by processing the original dataset. Retrieved from https://preview.grid.unep.ch/index.php?preview=data&events=droughts&evcat=1&lang=eng

Limitations: The data employed in the creation of this metric is historical and by nature is not predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by UNEP may not capture localized conditions of future landslide events and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in hazard but only to guide more localized decision-making considerations.

Map AC.10: Precipitation Changes for the End of the Century (with climate change) (MIROC-ESM-CHEM MODEL)



This layer shows the expected changes in precipitation for the end of the century. The model behind this map considers variations due to climate change under Representative Concentration Pathway (RCP) 8.5 and Global Climate Model MIROC-ESM-CHEM.

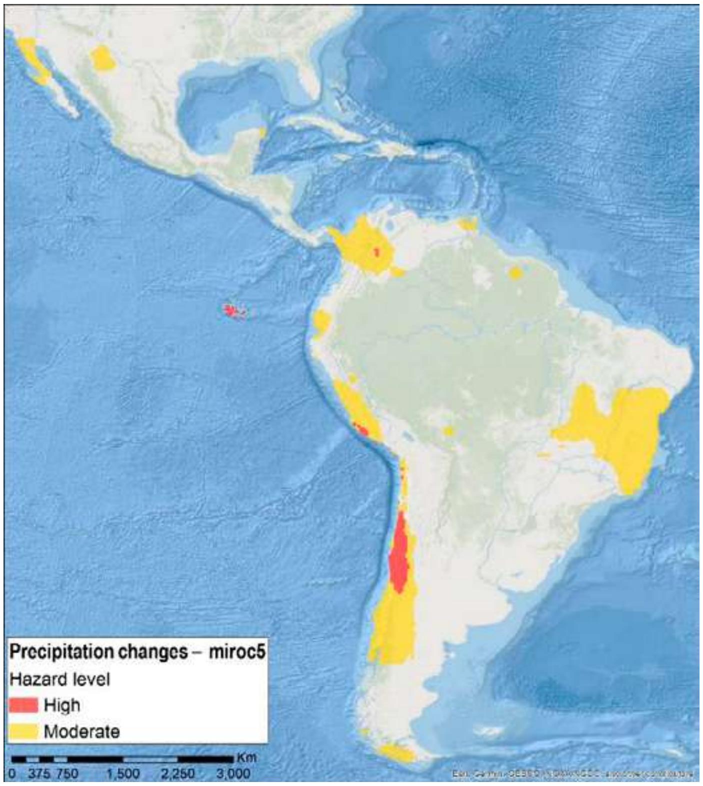
This layer shows the change in expected precipitation for the end of the century, considering climate change (percentage change in precipitation for the period 2070–2099 relative to the period 1976–2005 using the MIROC-ESM-CHEM model). Percentage changes between -25 percent and +25 percent are considered "low," percentage changes between -50 percent and -25 percent or between +25 percent and +50 percent are considered "moderate," and percentage changes greater than -50 percent or +50 percent are considered "high."

This 25-km resolution layer considers climate change impact on precipitation patterns. It was created from global future precipitation data (NASA Earth Exchange Global Daily Downscaled Projections, or NEX-GDDP) that would allow a user to identify areas that may be subject to major changes in precipitation patterns based on one of five selected Global Climate Model (GCM) precipitation datasets: "MIROC-ESM-CHEM" (this model is the result of research conducted by the Japan Agency for Marine-Earth Science and Technology, the Atmosphere and Ocean Research Institute and the Center for Climate System Research - National Institute for Environmental Studies). This model includes components of the atmosphere, ocean, sea-ice, land-surface, ocean and terrestrial biogeochemistry, and atmospheric chemistry and aerosols. It represents the estimations of precipitation change (percentage change) employing the RCP 8.5, the historic baseline 1976–2005 and future time period 2070–2099.

Data source: NEX-GDDP. 2017. Data Access. Precipitation Changes – End of Century MIROC-ESM-CHEM. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric is from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heatwave impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.11: Precipitation Changes for the End of the Century (with climate change) (MIROC5 MODEL)



This layer shows the expected changes in precipitation for the end of the century. The model behind this map considers variations due to climate change under Representative Concentration Pathway (RCP) 8.5 and Global Climate Model MIROC-5.

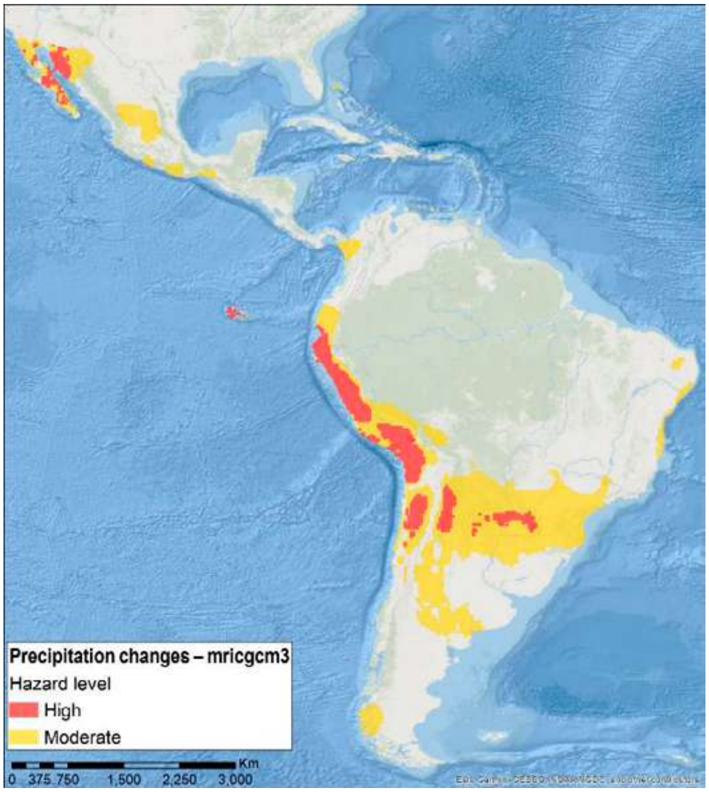
This layer shows the change in expected precipitation for the end of the century, considering climate change (percentage change in precipitation for the period 2070–2099 relative to the period 1976–2005 using the MIROC5 model). Percentage changes between -25 percent and +25 percent are considered "low," percentage changes between -50 percent and -25 percent or between +25 percent and +50 percent are considered "moderate," and percentage changes greater than -50 percent or +50 percent are considered "high."

This 25-km resolution layer considers climate change impact on precipitation patterns. It was created from global future precipitation data (NASA Earth Exchange Global Daily Downscaled Projections, or NEX-GDDP) that would allow a user to identify areas that may be subject to major changes in precipitation patterns based on one of five selected Global Climate Model (GCM) precipitation datasets: MIROC5 (this model is the result of research conducted by the Japan Agency for Marine-Earth Science and Technology, the Atmosphere and Ocean Research Institute and the Center for Climate System Research - National Institute for Environmental Studies). This is an atmosphere-ocean general circulation model. It represents the estimations of precipitation change (percentage change) employing the RCP 8.5, the historic baseline 1976–2005 and future time period 2070–2099.

Data source: NEX-GDDP. 2017. Data Access. Precipitation Changes – End of Century MIROC5. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric is from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heat wave impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.12: Precipitation Changes for the End of the Century (with climate change) (MRICGGCM3 MODEL)



This layer shows the expected changes in precipitation for the end of the century. The model behind this map considers variations due to climate change under Representative Concentration Pathway (RCP) 8.5 and Global Climate Model MRI-CGCM3.

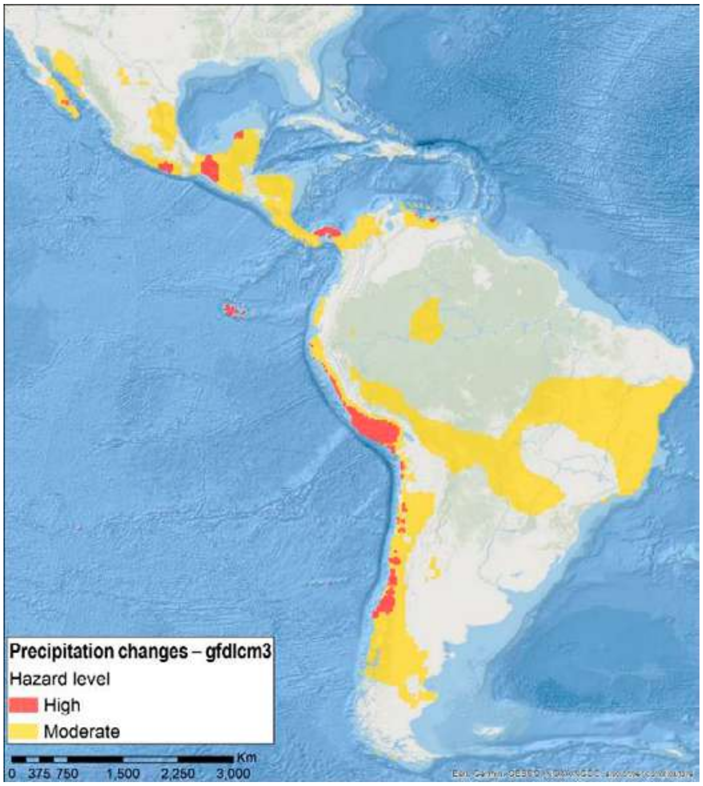
This layer shows the change in expected precipitation for the end of the century, considering climate change (percentage change in precipitation for the period 2070–2099 relative to the period 1976–2005 using the MRI-CGCM3 model). Percentage changes between -25 percent and +25 percent are considered "low," percentage changes between -50 percent and -25 percent or between +25 percent and +50 percent are considered "moderate," and percentage changes greater than -50 percent or +50 percent are considered "high."

This 25-km resolution layer considers climate change impact on precipitation patterns. It was created from global future precipitation data (NASA Earth Exchange Global Daily Downscaled Projections, or NEX-GDDP) that would allow a user to identify areas that may be subject to major changes in precipitation patterns based on one of five selected Global Climate Model (GCM) precipitation datasets: "MRI-CGCM3" (this model is the result of research conducted by the Japan Agency for Marine-Earth Science and Technology, the Atmosphere and Ocean Research Institute and the Center for Climate System Research - National Institute for Environmental Studies). This is an atmosphere-ocean general circulation model. It represents the estimations of precipitation change (percentage change) employing the RCP 8.5, the historic baseline 1976–2005 and future time period 2070–2099.

Data source: NEX-GDDP. 2017. Data Access. Precipitation Changes – End of Century MRI-CGCM3. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric is from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heat wave impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.13: Precipitation Changes for the End of the Century (with climate change) (GFDL-CM3 MODEL)



This layer shows the expected changes in precipitation for the end of the century. The model behind this map considers variations due to climate change under Representative Concentration Pathway (RCP) 8.5 and Global Climate Model GFDL-CM3.

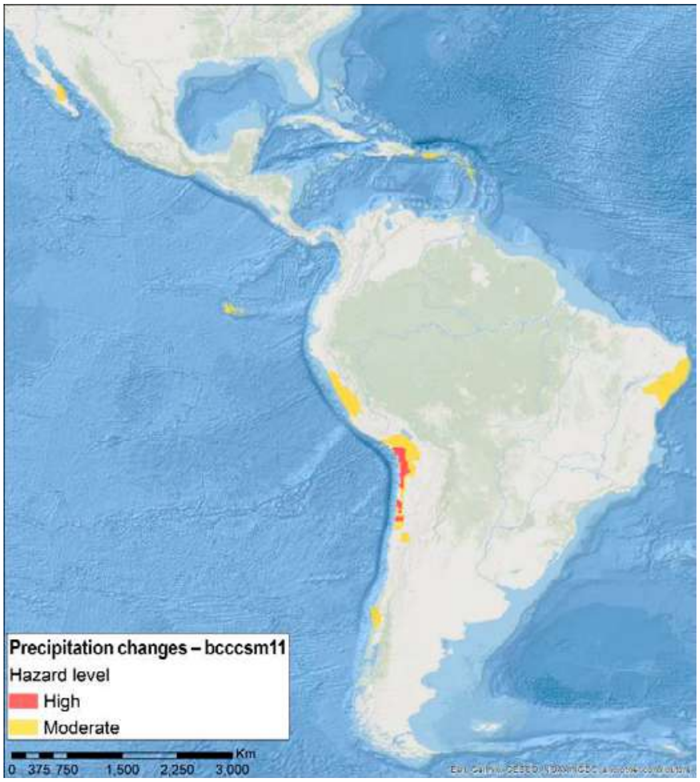
This layer shows the change in expected precipitation for the end of the century, considering climate change (percentage change in precipitation for the period 2070–2099 relative to the period 1976–2005 using the GFDL-CM3 model). Percentage changes between -25 percent and +25 percent are considered "low," percentage changes between -50 percent and -25 percent or between +25 percent and +50 percent are considered "moderate," and percentage changes greater than -50 percent or +50 percent are considered "high."

This 25-km resolution layer considers climate change impact on precipitation patterns. It was created from global future precipitation data (NASA Earth Exchange Global Daily Downscaled Projections, or NEX-GDDP) that would allow a user to identify areas that may be subject to major changes in precipitation patterns based on one of five selected Global Climate Model (GCM) precipitation datasets: "GFDL-CM3" (this model is the result of research conducted by the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration). It represents the estimations of precipitation change (percentage change) employing the RCP 8.5, the historic baseline 1976–2005 and future time period 2070–2099.

Data Source: NEX-GDDP. 2017. Data Access. Precipitation Changes – End of Century GFDL-CM3. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric is from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heat wave impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.14: Precipitation changes for the End of the Century (with climate change) (BCCCSM11 MODEL)



This layer shows the expected changes in precipitation for the end of the century. The model behind this map considers variations due to climate change under Representative Concentration Pathway (RCP) 8.5 and Global Climate Model BCC-CSM11.

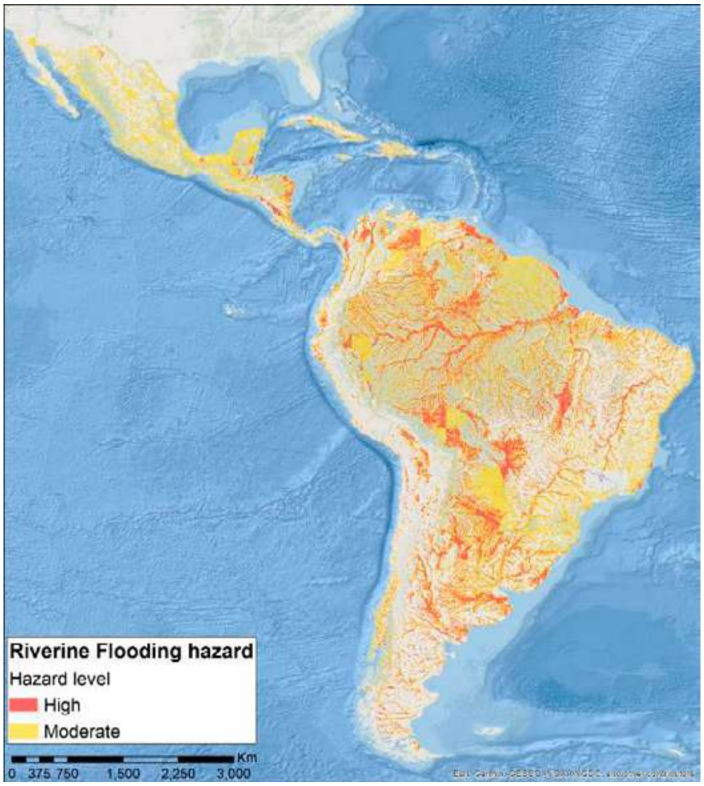
This layer shows the change in expected precipitation for the end of the century, considering climate change (percentage change in precipitation for the period 2070–2099 relative to the period 1976–2005 using the BCC-CSM11 model). Percentage changes between -25 percent and +25 percent are considered "low," percentage changes between -50 percent and -25 percent or between +25 percent and +50 percent are considered "moderate," and percentage changes < -50 percent or > +50 percent are considered "high."

This layer considers climate change impact on precipitation patterns. It was created from global future daily precipitation data (NASA Earth Exchange Global Daily Downscaled Projections, or NEX-GDDP) that would allow a user to identify areas that may be subject to major changes in precipitation patterns based on one of five selected Global Climate Model (GCM) precipitation datasets: "BCC-CSM11" (this model is the result of research conducted by the Beijing Climate Center). This is a fully coupled global climate-carbon model. It represents the estimations of precipitation change (percentage change) employing the RCP 8.5, the historic baseline 1976–2005 and future time period 2070–2099.

Data source: NEX-GDDP. 2017. Data Access. Precipitation Changes – End of Century BCC-CSM11. Created by the IDB by processing the original dataset. Retrieved from https://cds.nccs.nasa.gov/nex-gddp/

Limitations: The data employed in the creation of this metric is from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (25-kilometer resolution) may not capture localized conditions of future heat wave impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.15: Riverine Flooding Hazard



This layer shows riverine flooding hazard. The model behind this map does not consider variations due to climate change (that is, it assumes there will be no significant change in time in the way the hazard has presented itself historically).

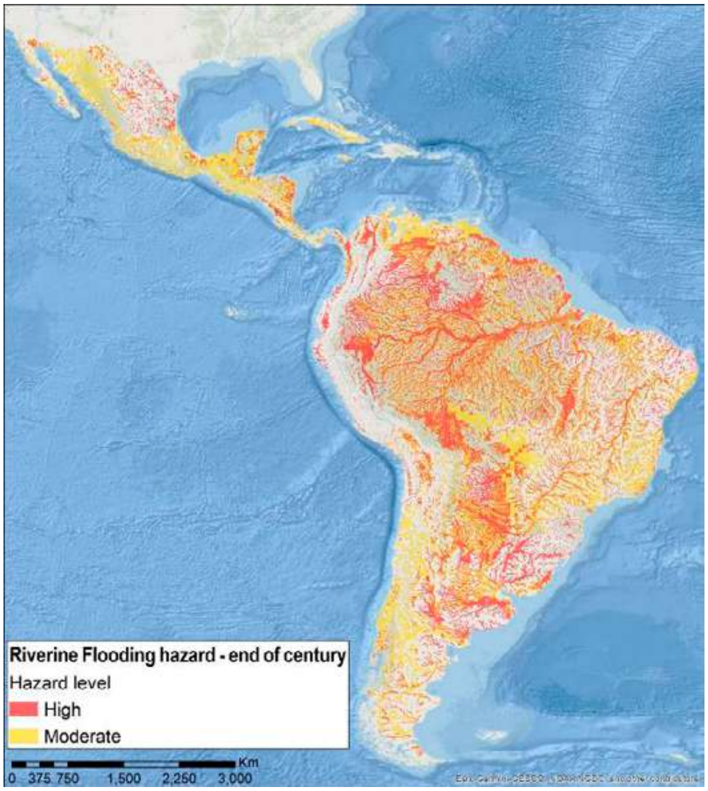
This layer shows the hazard map for riverine flooding. Areas within the 25-yr return period map extent are considered “high” risk; areas between the 50 and 100-yr extents are considered “moderate” risk; all other areas are considered “low” risk.

This layer was created using the model output from the UNISDR Global Assessment Report on Risk Reduction 2015 (GAR 15) global flood hazard assessment; this model uses historical data and a river overflow model to obtain flood hazard maps for 6 return periods (25, 50, 100, 200, 500 and 1000). A gridded dataset of low-sloped areas (<5 percent) derived from a 30-meter resolution Digital Elevation Model (DEM) produced by NASA’s Shuttle Radar Topography Mission (SRTM) was used to downscale the 1-km gridded GAR 15 dataset for more accurate flood hazard mapping, but spatially limited to the extents of the 1-km gridded GAR 15 dataset.

Data source: UNISDR (United Nations International Strategy for Disaster Reduction). s.d. GAR Atlas: Global Assessment Report on Disaster Risk Reduction - Risk Data Platform. Flood hazard 25, 50 and 100 years [raster geospatial data flood_25_g1510, flood_50_g1511 and flood_100_g157]. Riverine Flooding Hazard. Created by the IDB by processing the original dataset. Retrieved from https://risk.preventionweb.net/capraviewer/download.jsp?tab=9&mapcenter=0,1123252.6982849&mapzoom=2

Limitations: The data employed in the creation of this metric is historical and based on probabilistic modeling approaches and by nature is not predictive of where future hazards will be experienced or found. Additionally, even with the downscaling using NASA SRTM DEM data, the scale of the data provided by UNEP GAR 15 may not capture localized effects of riverine flood events and therefore should not be used to represent areas of inundation or impact expected from future events. Data provided are meant to offer general trends in Hazard but only to guide more localized decision-making considerations.

Map AC.16: Riverine Flooding Hazard: End of the Century (with climate change)



This layer shows the map for riverine flooding hazard for the end of the century, considering climate change.

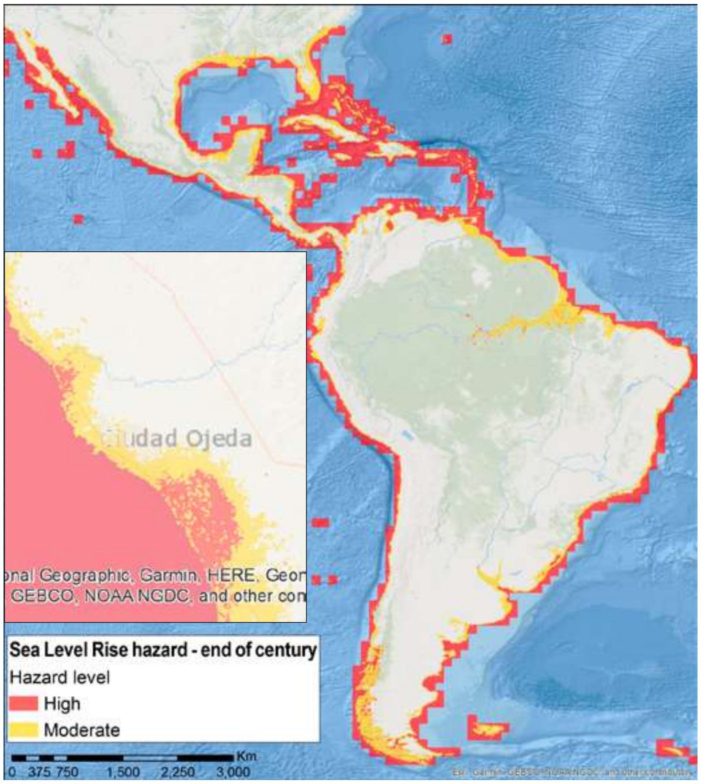
This layer was created using several global datasets. The first step involved estimating future change (positive, negative, or no change) in flood hazard using the methodology outlined by Dankers et al. (2014); this resulted in a future flooding layer with a 55km resolution representing the percentage change in the 30-year return flow - Q30 – of rivers for the period 2070–2099 relative to the period 1971–2000 (where percentage changes between -100 percent and +10 percent are considered "low," changes between +10 percent and 20 percent are considered "moderate," and changes greater than +20 percent are considered "high"). Next, this layer was processed together with the stationary flood hazard layer (without climate change) applying the following procedure: first, the overall extent of the moderate and high-hazard areas of the stationary layer was expanded in all directions by 1 kilometer (the reasoning for this is that even areas that may have an estimated decrease in the Q30 may still experience more intense storm events under future climate conditions and therefore experience wider extents of flooding); second, the areas already identified as moderate or high in the stationary layer, and that are identified as moderate under the 55km-resolution future layer, remained unchanged in their the hazard level; and third, the areas already identified as moderate or high in the stationary layer, and that are identified as high under the 55km-resolution future layer, were reclassified as high. A gridded dataset of "low-sloped" areas (<5 percent) derived from the 30-meter resolution Digital Elevation Model produced by NASA's Shuttle Radar Topography Mission (SRTM) was used to downscale the 1-km gridded GAR 15 dataset for more accurate probable flood hazard mapping, but spatially limited to the extents of the 1-km gridded GAR 15 dataset, buffered by 2 kilometers.

This layer must be read together with the stationary flooding hazard layer (without considering climate change) to evaluate, first, the hazard levels without climate change and, second, how these hazard levels change for the end of the century once climate change is included (they are directly comparable because the future layer used the stationary layer as a basis for its computation).

Data source: ISIMIP (Inter-Sectoral Impact Model Intercomparison Project). 2017. Fast Track data archive. Riverine Flooding Hazard –End of the Century (with Climate Change). Created by the IDB by processing the original dataset. Retrieved from https://esg.pik-potsdam.de/search/isimip-ft/

Limitations: The data employed in the creation of this metric is from both historic and forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by ISIMIP (~55-kilometer resolution) and UNISDR GAR 15 DATA (1-kilometer resolution) may not capture localized conditions of future flooding impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in hazard but only to guide more localized decision-making considerations.

Map AC.17: Sea Level Rise Hazard



This layer shows the sea level rise hazard for the end of the century. The model behind this map considers variations due to climate change.

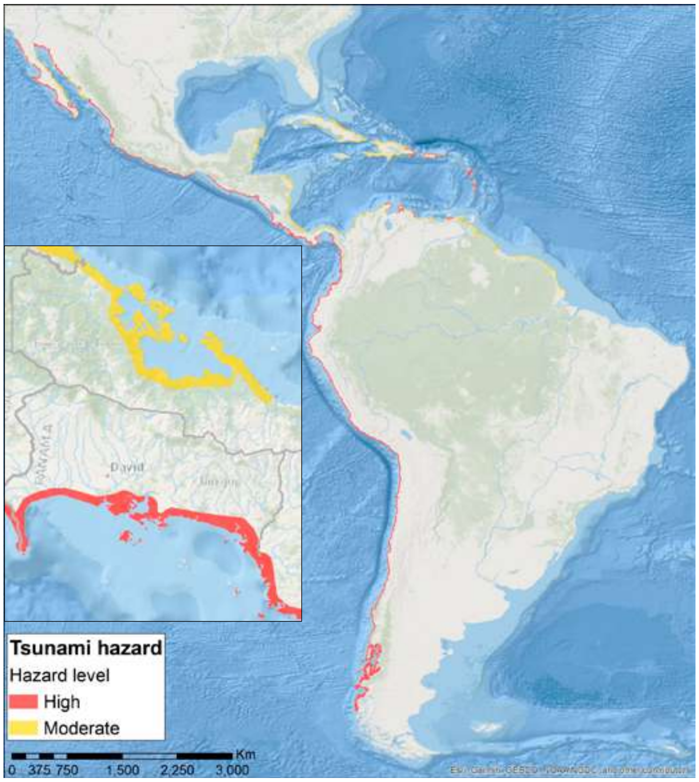
This layer shows the map for future sea level rise hazard (hazard levels were determined using only terrain elevation). Land elevations above sea level up to 0.61 meters (2 feet) are considered "high"; land elevations between 0.61 meters (2 feet) and 1.22 meters (4 feet) are considered "moderate," land elevations greater than 1.22 meters (4 feet) are considered "low." The areas identified as "moderate" and "high" for this hazard were limited to areas within 100 km of existing tidally influenced (i.e., coastal) areas.

This layer was created from a global dataset allowing users to identify areas that may be subject to inundation due to future rise of sea/ocean levels. It was created using a 30-meter resolution Digital Elevation Model produced by NASA's Shuttle Radar Topography Mission (SRTM). The land elevation thresholds selected were based on the 2014 U.S. National Climate Assessment (conservative) estimates that sea level will rise another 0.3 meters – 1.22 meters (1 ft - 4 ft), perhaps 1.83 meters (6 feet) by the end of century (2100).

Data source: NASA (National Aeronautics and Space Administration). 2017. NASA's Land Processes Distributed Active Archive Center. SRTM. Sea Level Rise Hazard. Created by the IDB by processing the original dataset. Retrieved from https://e4ftl01.cr.usgs.gov/

Limitations: The data employed in the creation of this metric is from existing data and by nature is not predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by NASA (30-meter resolution) may not capture localized conditions of future sea level rise impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.18: Tsunami Hazard



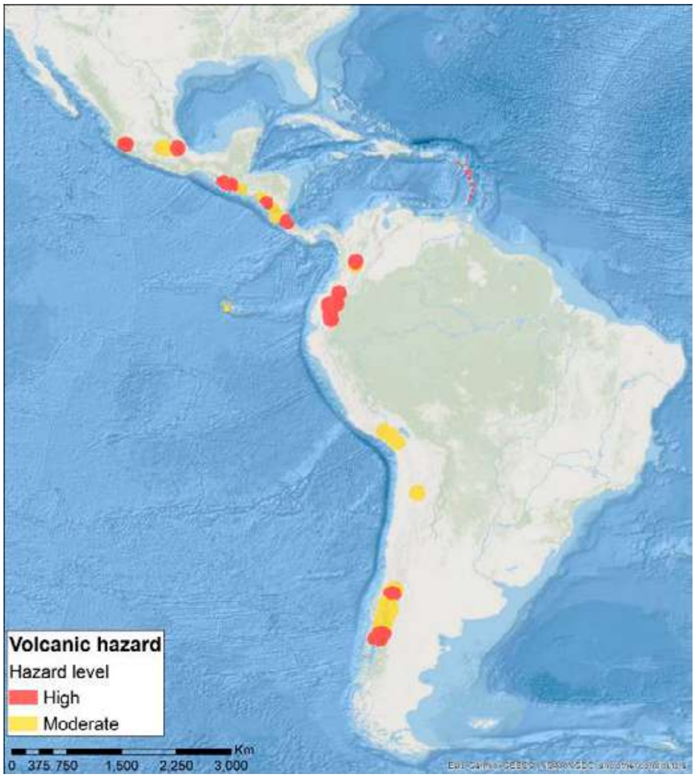
This layer shows the probabilistically integrated hazard map for water run-up height (maximum vertical height onshore above mean sea level reached by the water – in meters) for a return period of 475 years. Run-up values below 0.1 m are considered "low," run-up values between 0.1 m and 2 m (inclusive) are considered "moderate," run-up values greater than 2 m are considered "high." The areas identified as "moderate" and "high" were limited to areas within 5 km of existing tidally influenced (i.e., coastal) areas.

This layer was created from a global dataset of points that were buffered to create a zone of approximately 5 kilometers inland from coast lines—allowing users to identify areas that may be subject to run-up surges from tsunamis. The data corresponds to the output from the probabilistic tsunami hazard model built for the UNISDR Global Assessment Report on Risk Reduction 2015 (GAR 15) global risk assessment. This hazard model applies historical data and predictive modeling efforts to obtain a set of stochastically simulated events that represents an exhaustive collection of all the events that could ever happen; this set not only respects past behaviors but also includes extreme events that have not necessarily occurred yet and that can still occur. This model was created by the Norwegian Geotechnical Institute and Geoscience Australia, (NGI and GA, 2014). For more details see Cardona et al. (2015) and Lovholt et al. (2014).

Data source: UNISDR (United Nations International Strategy for Disaster Reduction). s.d. GAR Atlas: Global Assessment Report on Disaster Risk Reduction - Risk Data Platform. Tsunami Hazard (Run up) RP 475 years [shapefile geospatial data Tsunami_hazard_results_g1545]. Tsunami Hazard. Created by the IDB by processing the original dataset. Retrieved from https://risk.preventionweb.net/capraviewer/download.jsp?tab=9&mapcenter=0,1123252.6982849&mapzoom=2

Limitations: While these data are not merely historical but involve predictive modeling, they still should not be considered predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by UNEP may not capture localized conditions of future tsunami events and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in hazard but only to guide more localized decision-making considerations.

Map AC.19: Volcanic Hazard



This layer shows the map for volcanic hazard (the index shown by this map is the Volcano Hazard Index (VHI)). VHI values equal to 0 or 1 are considered "low," VHI values equal to 2 are considered "moderate," VHI values equal to 3 are considered "high."

This layer was created from a global dataset containing a point coverage representing volcanoes with historic activity. The point coverage was buffered 100 km in all directions allowing users to identify areas that may be subject to volcanic activity. When two differently ranked point buffers overlapped, the highest of the two layers was given precedence. The source data for this layer corresponds to the VHI as provided to UNISDR by The International Association of Volcanology and Chemistry of the Earth's Interior. This work is the first of its kind in global coverage and level of contribution from a wide network of experts and institutions around the world.

Data source: UNISDR (United Nations International Strategy for Disaster Reduction). s.d. GAR Atlas: Global Assessment Report on Disaster Risk Reduction - Risk Data Platform. Location of active and inactive volcanoes [shapefile geospatial data Volcano_g1546]. Volcanic Hazard. Created by the IDB by processing the original dataset. Retrieved from https://risk.preventionweb.net/capraviewer/download.jsp?tab=9&mapcenter=0,1123252.6982849&mapzoom=2

Limitations: The data employed in the creation of this metric is historical and by nature is not predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by UNISDR may not capture localized conditions of future volcanic events and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.20: Water Scarcity Hazard

This layer shows the water scarcity hazard for the end of the century. The model behind this map considers variations due to climate change.

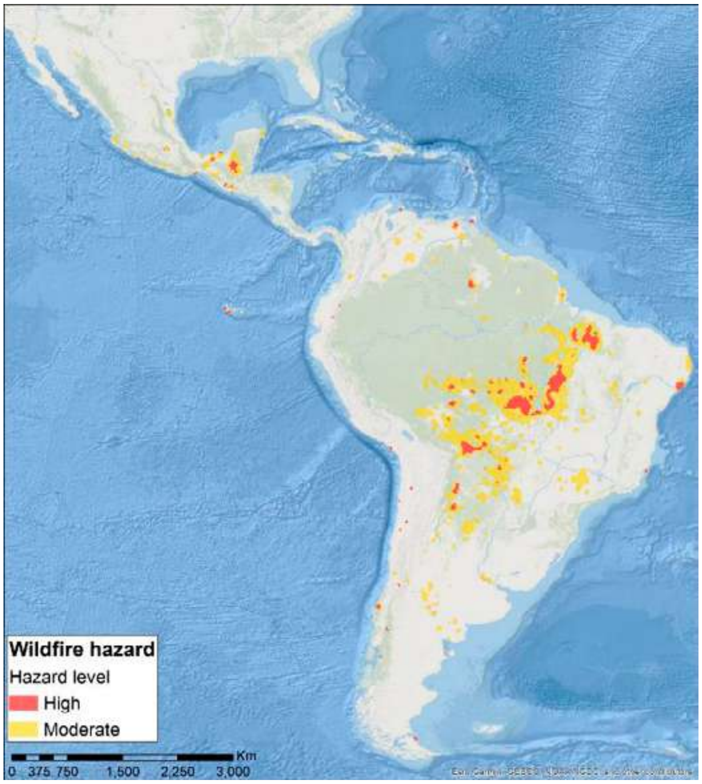
This layer shows the change in water scarcity hazard for the end of the century, considering climate change (percentage change in precipitation for the future relative to 1980–2010). Percentage changes between -100 percent and -20 percent are considered "high"; percentage changes between -20 percent and -10 percent are considered "moderate," percentage changes > -10 percent are considered "low."

This ~55 km resolution layer considers climate change impacts on water supply and was created by estimating future change (positive, negative, or no change) in precipitation amounts associated with an average warming of 2°C as explained by Schewe et al. (2014). Monthly precipitation data from 10 global impact models (GIMs) and 5 global climate models (GCMs) from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Fast Track data archive was used to estimate the percentage change in precipitation under future conditions compared to that during historic conditions (1980–2010). Water scarcity is presented in terms of ensemble mean change in precipitation between the historic and future conditions across all GIM-GCM combinations.

Data source: ISIMIP. 2017. Fast Track data archive. Water Supply Scarcity Hazard – End of the Century (with Climate Change). Created by the IDB by processing the original dataset. Retrieved from https://esg.pik-potsdam.de/search/isimip-ft/

Limitations: The data employed in the creation of this metric is from forecasted models and data and may not be predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by ISIMIP (~55-kilometer resolution) may not capture localized conditions of future water supply scarcity impacts and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in probability for this hazard but only to guide more localized decision-making considerations.

Map AC.21: Wildfire Hazard



This layer shows the wildfire hazard. The model behind this map does not consider variations due to climate change (that is, it assumes there will be no significant change in time in the way the hazard has presented itself historically).

This layer shows the map for wildfire hazard (the index shown by this map is the expected average number of wildfire events per 0.1 decimal degree pixel, per year, multiplied by 100 - i.e. a 64 value means 0.64 events per year). Index values below 50 are considered "low," values between 50 and 75 (inclusive) are considered "moderate," values above 75 are considered "high."

This layer was created from a 10-km resolution gridded global dataset that would allow a user to identify areas that may be subject to wildfires based on historical data. The data corresponds to the output from the wildfire hazard assessment done for the UNISDR Global Assessment Report on Risk Reduction 2009 (GAR 09) global risk assessment. It is based on a dataset that estimates an average of fires density over the period 1997–2010. It is based on the modified algorithm-1 product of the World Fire Atlas (WFA, ESA-ESRIN) dataset. UNEP/GRID-Europe compiled the monthly data and processed the global fire density.

Data source: UNEP (United Nations Environment Programme) and UNISDR (United Nations International Strategy for Disaster Reduction). 2014. Global Risk Data Platform. Fires – Density [raster geospatial data fi_average_tiff]. Wildfire Hazard. Created by the IDB by processing the original dataset. Retrieved from https://preview.grid.unep.ch/index.php?preview=data&events=fires&evcat=3&lang=eng

Limitations: The data employed in the creation of this metric is historical and by nature is not predictive of where future hazards will be experienced or found. Additionally, the scale of the data provided by UNEP may not capture localized conditions of future wildfire events and therefore should not be used to represent areas affected by future events. Data provided are meant to offer general trends in Hazard but only to guide more localized decision-making considerations.

References, Appendix C

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UNISDR, s.d.: the full reference was theer in the text: UNISDR (United Nations International Strategy for Disaster Reduction). n.d.. Global Risk Data Platform. Storm Surge Hazard 250 years [Shapefile geospatial data storm_surge_hazard_shapefile]. Hurricane Storm Surge Hazard. Created by the IDB by processing the original dataset. Retrieved from https://preview.grid.unep.ch/index.php?preview=data&events=gar2015&evcat=37&metaid=179&lang=eng

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D. 2014. First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble, Proc. Natl. Acad. Sci., 111, 3257–3261, doi:10.1073/pnas.1302078110. Available at https://www.pnas.org/content/111/9/3257

Schewe et al., 2014: Schewe, J., J. Heinke, D. Gerten, I. Haddeland, N. W. Arnell, D. B. Clark, R. Dankers, S. Eisner, B. M. Fekete, F. J. Colón-González, S. N. Goslin, H. Kim, X. Liu, Y. Masaki, F. T. Portmann, Y. Satoh, T. Stacke, Q. Tang, Y. Wada, D. Wisser, T. Albrecht, K. Frieler, F. Piontek, L. Warszawski, and P. Kabat. 2014. Multimodel assessment of water scarcity under climate change. PNAS, 111 (9), pp. 3245 – 3250. Available at https://www.pnas.org/content/111/9/3245

Appendix AC.1: How to Read and Interpret Climate Change Layers

For some of the hydrometeorological hazards there are two (or more) layers representing the hazard with and without the effect of climate change. For other hazards there is only a single layer representing the effect of climate change. Most of these layers present the projections under RCP 8.5 (pessimistic scenario) by the end of the century (2100); this is to ensure that the “signal” of climate change is captured (optimistic and shorter-term scenarios could miss the signal of change, which is all that is needed for screening purposes, as this is not a detailed assessment to be used directly in the project design). Each of these cases is described next.

Sea Level Rise

Given that this hazard exists only because of climate change, this layer is stand alone; that is, it does not have a sister stationary layer to represent the hazard without the effect of climate change. Thus, this layer should be read by itself to determine if sea level rise due to climate change is an issue.

Precipitation Changes

Although precipitation is not a hazard by itself, it is a climate variable of interest that can be used to infer hazards such as urban flooding. Precipitation is one of the variables that GCMs find the hardest to predict with confidence, thus in general the predictions provided by all GCMs carry considerably uncertainty. To manage this, it is recommended that multiple GCMs are consulted (this is called using a multi-model ensemble) and only the trends that are consistent in most of the models of the ensemble are considered robust. Thus, the projections from five GCMs (the page on each layer provides details on the names and origins of these models) have been included. These models should all be read together, and it should be determined if most (three or more) of them show the same trend for the project area. If so, then there is an issue with precipitation that should be flagged; otherwise nothing can be concluded with confidence.

Riverine Flooding Hazard

This hazard has two sister layers that should be read together. The first is a stationary layer where the hazard was modeled without considering the effects of climate change. The second layer shows the result of including climate change effects into the hazard modeling. The two layers should be read together to evaluate, first, the hazard levels without climate change and, second, how these hazard levels change by the end of the century.

Heat Wave Hazard

This hazard has three sister layers that should be read together. The first one is a stationary layer where the hazard was modeled without considering the effects of climate change. The other two layers show the result of including climate change effects into the hazard modeling, and as a result show the effect of climate change under RCP 4.5 (optimistic scenario) and 8.5 (pessimistic scenario), respectively. The 4.5 scenario is included just to provide an additional more optimistic perspective. The three layers should be read together to evaluate, first, the hazard levels without climate change and, second, how these hazard levels change for the end of the century under RCPs 4.5 and 8.5 (all layers use the same data and modeling, so they are directly comparable).

Drought Hazard

This hazard has two sister layers that should be read together. The first one is a stationary layer where the hazard was modeled without considering the effects of climate change. The second layer shows the result of including climate change effects into the hazard modelling. The two layers should be read together to evaluate, first, the hazard levels without climate change and, second, the magnitude of the expected change (in this case, increase) in drought hazard by the end of the century once climate change is included

Appendix D: Hazard Software

Flood

Table AD.1. Coastal Flood Models

Program	Developed by	Available from	Public Domain?	Description
		Hydrodynamics flood/surge models		
DELFT3D FM	Deltares	Rotterdamseweg 185,2629 HD, Delft, The Netherlands XP PO Box: P.O. Box 177, 2600 MH Delft, The Netherlands	No	This model is the next generation of DELFT3D hydrodynamical simulations module on unstructured grids in 1D-2D-3D. DELFT3D FM simulates storm surges, hurricanes, tsunamis, detailed flows and water levels, waves, sediment transport and morphology, and water quality and ecology. Type: Component of Delft3D Model
Dynamic Behavior of Tidal Flow at InNLETs (DYNLET)	U.S. Army Corps of Engineers (USACE)	Coastal and Hydraulics Laboratory Engineering Research and Development Center	Yes	This program is a one-dimensional model of dynamic behavior of tidal flow at inlets. It can be used to predict tide-dominated velocities and water-level fluctuations at an inlet and interior back bay system. DYNLET solves the full one-dimensional shallow water equations using an implicit finite difference solution. Type: Model
FEMA Surge (1988)	Tetra Tech, Inc.; Engineering Methods & Applications; Greenhorne & O'Mara; Camp, Dresser & McKee, Inc.	Federal Emergency Management Agency	Yes	This model incorporates modified NWS-23 model for hurricanes and Joint Probability Method and simulates surges caused by hurricanes. It is reportedly more accurate for water elevations than water currents and includes non-standard features such as barrier islands, roadways, and channels. Type: Model

Program	Developed by	Available from	Public Domain?	Description
MOHID	MARETEC (Superior Technician Institute for the Lisbon University)	Departamento de Engenharia Mecânica / Mechanical Engineering Department	Freeware	MOHID is a three-dimensional water modelling system that allows the simulation of processes (physical and biogeochemical) in different systems (estuaries and watersheds) and scales (allowing the use of nested models). Some processes may be coupled with atmospheric processes. Type: Model
SOBEK	Deltares	Deltares	No	SOBEK is a modelling suite for 1D/2D flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt intrusion and surface water quality. SOBEK-River is the product line designed for river systems and estuaries. Type: Model
TABS RMA2 v. 4.3 and up (Oct. 1996)	USACE	Coastal Engineering Research Center Department of the Army Waterways Experiment Station Corps of Engineers	Yes	TABS RMA2 v 4.3 is a two-dimensional steady/unsteady flow model that simulates water levels and velocities. The model computes finite element solutions of the Reynolds form of the Navier-Stokes equations for turbulent flows. Type: Model
		Coastal wave height models		
BOUSS-2D	Aquaveo, LLC	Aquaveo	No	BOUSS-2D is used for simulating the propagation and transformation of waves in coastal regions and harbors, over small regions (generally 1-5 km). The program successfully models nearshore zone and harbor phenomena, including shoaling, refraction, diffraction, full/partial reflection and transmission, bottom friction, nonlinear wave-wave interactions, wave breaking and runup, wave-induced currents, and wave-current interaction. Type: Model; used with Surface-water Modeling System (SMS) software for 3-D rendering

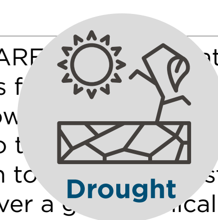
Program	Developed by	Available from	Public Domain?	Description
CHAMP 2.0 (April 2007)	Dewberry & Davis LLC	Federal Emergency Management Agency	Yes	Coastal Hazard Analysis Modeling Program (CHAMP) is a Windows-based program used for erosion and wave height analyses (WHAFIS 4.0 and RUNUP 2.0) and provides summary tables and graphics for mapping. Version 2.0 provides for computation of 1% - and 0.2%-annual-chance wave envelope and includes enhancements to the Erosion and Runup Modules. Type: Model
FUN-WAVE-TVD	Fengyan Shi, James T. Kirby and Babak Tehranirad, Jeffrey C. Harris	Fengyan Shi	Freeware	FUNWAVE–TVD is an improved version of the fully nonlinear Boussinesq wave model (FUNWAVE) initially developed by Kirby et al. (1998). This model simulates nearshore surface-waves, currents and tsunamis from ocean-basin to nearshore scales. Type: Model
RCPWAVE -1986	USACE	Coastal Engineering Research Center Department of the Army Waterways Experiment Station Corps of Engineers	Yes	Regional Coastal Processes WAVE is a regional coastal processes wave model that simulates wave propagation over specified bathymetry. The model treats linear, monochromatic waves propagating over grid giving coastal bathymetry and provides nearshore wave heights pertinent to proper spacing between transects or to magnitudes of wave setup. Type: Model
REF/DIF	UDEL/Jim Kirby	University of Delaware, Center for Applied Coastal Research	Freeware	REF/DIF is a phase-resolving parabolic refraction-diffraction model for ocean surface wave propagation. This model can simulate the effects of shoaling, refraction, diffraction, and energy dissipation, while wave reflection and wave-wave interaction are neglected. Accurate results are restricted to waves propagating on a mild bottom slope within 45° from the mean wave direction. Type: Model
Simulating Waves Nearshore (SWAN), Cycle III Version 40.51	The SWAN team	Source Forge	Freeware	SWAN is a fully spectral (in all directions and frequencies) third-generation shallow water wave model based on the wave action balance equation with sources and sinks. The model is used for obtaining estimates of wave parameters in coastal areas, lakes and estuaries from win, bottom and current conditions. Type: Model

Program	Developed by	Available from	Public Domain?	Description
STWAVE	USACE	Aquaveo	No	STWAVE is a steady-state, finite difference, spectral model based on the wave action balance equation. The model provides a flexible and robust model for nearshore wind-wave growth and propagation. STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wave growth because of wind input, and wave-wave interaction. Type: Model; used with Surface-water Modeling System software for 3-D rendering.
Wave Watch 3 (WW3)	NOAA/NWS/ NCEP	National Oceanic and Atmospheric Administration, Environmental Modeling Center	Freeware	WW3 is a wave model that simulates wave fields using the directional spectra of wave number. Type: Model
WHAFIS 3.0 (1988) and 4.0 (2007)	Dames & Moore, revised by Greenhorne & O'Mara, revised by Watershed Concepts	Federal Emergency Management Agency	Yes	Wave Height Analysis for Flood Insurance Studies (WHAFIS) 4.0 is a model developed to predict wave heights associated with hurricane coastal storm surge. The model has identical wave treatments as WHAFIS 3.0. WHAFIS 3.0 defines wave heights associated with 100-year flood in coastal areas using modern wave action treatment; it incorporates 1977 NAS recommendations on basic approximations for wind speeds, wave breaking criterion, and controlling wave height. Type: Model
Coastal wave effects models				
ACES 1.07 (1992)	USACE	Coastal Engineering Research Center Department of the Army Waterways Experiment Station Corps of Engineers 3909 Halls Ferry Road Vicksburg, MS 39180-6199	Yes	Automated Coastal Engineering System (ACES) conducts an extreme wave height analysis and is used to calculate runup and overtopping against vertical and sloping structures or revetment. Type: Model containing seven categorical applications.

Program	Developed by	Available from	Public Domain?	Description
BOUSS-2D	Aquaveo, LLC	Aquaveo	No	BOUSS-2D is used for simulating the propagation and transformation of waves in coastal regions and harbors over small regions (generally 1-5 km). The program successfully models nearshore zone and harbor phenomena, including shoaling, refraction, diffraction, full/partial reflection and transmission, bottom friction, nonlinear wave-wave interactions, wave breaking and runup, wave-induced currents, and wave-current interaction. Type: Model; used with Surface-water Modeling System (SMS) software for 3-D rendering.
CHAMP 2.0 (April 2007)	Dewberry & Davis LLC	Federal Emergency Management Agency		Coastal Hazard Analysis Modeling Program (CHAMP) is a Windows-based program used for erosion and wave height analyses (WHAFIS 4.0 and RUNUP 2.0) and provides summary tables and graphics for mapping. Version 2.0 provides for computation of 1% and 0.2% annual-chance wave envelope and includes enhancements to the Erosion and Runup Modules. Type: Model
FUN-WAVE-TVD	Fengyan Shi, James T. Kirby and Babak Tehranirad, Jeffrey C. Harris	Fengyan Shi	Freeware	FUNWAVE–TVD is an improved version of the fully nonlinear Boussinesq wave model (FUNWAVE) initially developed by Kirby et al. (1998). This model simulates nearshore surface-waves, currents and tsunamis from ocean-basin to nearshore scales. Type: Model
IH-2VOF	IH Cantabria	IH Cantabria	No	IH2VOF models wave dynamics in the surf zone and against conventional and non-conventional coastal structures. Type: Model
REF/DIF	UDEL/Jim Kirby	University of Delaware, Center for Applied Coastal Research	Freeware	REF/DIF is a phase-resolving parabolic refraction-diffraction model for ocean surface wave propagation. This model can simulate the effects of shoaling, refraction, diffraction, and energy dissipation, while wave reflection and wave-wave interaction are neglected. Accurate results are restricted to waves propagating on a mild bottom slope within 45° from the mean wave direction. Type: Model

Program	**Developed by**	**Available from**	**Public Domain?**	**Description**
RUNUP 2.0 (1990)	Stone & Webster Engineering Corp., revised by Dewberry	See the footnote below to find appropriate contact information based on your FEMA Region 3	Yes	RUNUP 2.0 computes mean wave runup elevation for eight basic shore configurations per the 1978 guidance by USACE defining wave runup on shore barrier with specified approach and storm conditions. Type: Model
STWAVE	USACE	Aquaveo	No	STWAVE is a steady-state, finite difference, spectral model based on the wave action balance equation. The model provides a flexible and robust model for nearshore wind-wave growth and propagation. STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wave growth because of wind input, and wave-wave interaction. Type: Model; used with Surface-water Modeling System software for 3-D rendering.
Hydrodynamics, flood/surge models with coastal wave heights models				
Advanced Circulation Model (ADCIRC) 2DDI - 2003	Johannes Westerink, University of Notre Dame, and Rick Luettich, University of North Carolina at Chapel Hill, Institute of Marine Sciences for USACE Coastal and Hydraulics Laboratory	Nick Krauss (Coastal and Hydraulics Laboratory) Also can be purchased from software vendors as a component of SWM.	Available for flood insurance studies only	ADCIRC is a finite element 2-D hydrodynamic model that performs storm surge analyses through short- and long-term simulations of tide and storm surge elevations and velocities in deep-ocean, continental shelves, coastal seas, and small-scale estuarine system. Type: Model
DELFT3D	Deltares	Rotterdamseweg 185,2629 HD, Delft, The Netherlands PO Box: P.O. Box 177, 2600 MH Delft, The Netherlands	Freeware	Multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid or spherical coordinates. It includes wind stress forcing, Coriolis forcing, tidal potential, multiple boundary types, and has the ability to dynamically couple to Delft3D-Wave for wave-current interaction. For the wave propagation the Delft3D suit uses the SWAN Model. Type: Model

Program	Developed by	Available from	Public Domain?	Description
EFDC	Center for Exposure Assessment Modeling, U.S. Environmental Protection Agency (EPA)	EPA Center for Exposure Assessment Modeling	Freeware	The Environmental Fluid Dynamics Code is a multifunctional surface water modeling system, which includes hydrodynamic, sediment-contaminant, and eutrophication components. The model simulates water and water quality constituent transport in water bodies such as rivers, stratified estuaries, lakes, and coastal seas. Type: Model
MIKE 21 (HD/NHD) 2009 SP4	DHI Water and Environment	DHI, Inc. Agern Allé 5, Hørsholm 2970 Denmark +45 45169333 Telephone +45 45169292 Fax	No	MIKE 21 (HD/NHD) solves the non-linear depth-averaged equations of continuity and conservation of momentum in a two-dimensional, finite-volume, dynamic wind-wave growth and nearshore transformation model. It computes wave-driven currents and wave setup. The model includes a fully spectral formulation and a directional decoupled parametric formulation, includes wave-current interaction, as well as nearshore effects of refraction, shoaling, breaking, bed friction, and wind-wave growth. Type: Model component of MIKE 21 software
MIKE 21 FM HD 2014 SP3	DHI Water and Environment	DHI, Inc. Agern Allé 5, Hørsholm 2970 Denmark +45 45169333 Telephone +45 45169292 Fax	No	The program models hydrodynamics, waves, sediment dynamics, water quality and ecology in coastal or marine areas. The MIKE 21 FM HD is the unstructured complement to the rectangular finite difference version of the MIKE 21 HD model. The model utilizes an advanced flooding and drying algorithm for overland flow, and includes wind stress forcing, Coriolis forcing, tidal potential, and multiple boundary types. Type: Model component of MIKE 21 software
TELEMAC	TELEMAC-MASCARET Consortium	Open Telemac	Freeware	TELEMAC-MASCARE[illegible]t-ed suite of solvers f[illegible] of free-surface flow[illegible] ware dedicated to t[illegible] wave propagation to[illegible]st or into harbors, over a [illegible]ical domain of a few square km. Type: Software with multiple model simulations



Program	Developed by	Available from	Public Domain?	Description
XBEACH	Deltares	Deltares; University of Miami; UNESCO-IHE	Yes	XBEACH is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms. The model includes the hydrodynamic processes of shortwave transformation (refraction, shoaling, and breaking), long wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. Type: Model

Table AD.2. Drought Models

Program	Developed by	Available from	Public Domain?	Description
Standardized Precipitation Index	National Centers for Environmental Prediction	National Drought Mitigation Center, University of Nebraska	Yes	A tool for calculating the standardized precipitation index used for defining and monitoring drought. It determines the rarity of a drought at a given time scale for any rainfall station with historic data. Type: Tool
RMS Drought Stress Testing Tool	Global Canopy	Global Canopy	Freeware	The tool allows financial institutions to see how incorporating drought scenarios changes the perception of risk in their own loan portfolios. Based on the catastrophe modelling framework that the insurance industry has used for 25 years, it looks at five drought scenarios in four countries—Brazil, China, Mexico and the United States—to model the impact on 19 industry sectors, the companies in those sectors, and the likelihood that they will default on their loans. Type: Tool

Table AD.3. Earthquake Models

Program	Developed by	Available from	Public Domain?	Description
3D Focal Mechanisms	U.S Geological Survey (USGS)	USGS Western Earthquake Hazards Program	Yes	A tool within ArcScene that visually presents earthquake focal mechanisms, depth and magnitude of earthquakes. Type: Tool with ArcScene.
CAPRA-GIS	Central American Probabilistic Risk Assessment Platform (CAPRA)	CAPRA	Yes	A geographic information system (GIS)-based tool that uses a probabilistic approach to generate distributions of disaster risk and impacts based on vulnerability and exposure to various hazards. Type: Tool.
CRISIS 2007	National University of Mexico	CAPRA	Yes	A seismic and tsunami hazard model used for probabilistic hazard assessment and the calculation of stochastic scenarios for risk evaluation. Type: Model
Grazier-Kalkan (2015) Ground-Motion Prediction Equation	USGS	USGS - Earthquake Hazards Program	Yes	A model that predicts peak-ground acceleration and 5% damped pseudospectral acceleration for probabilistic and deterministic seismic hazard analyses. Type: Model
Ground Motion Prediction Equations (GMPE)	Global Earthquake Model (GEM)	OpenQuake - GEM	Freeware	A python and OpenQuake-based toolkit for analysis of strong motions and interpretations of GMPEs. Type: Toolkit
Hazard Curve Calculator	Open Seismic Hazard Analysis (OpenSHA)	OpenSHA and the University of Southern California	Freeware	A tool that computes and plots hazard curves for a specified Intensity Measure Type (IMT), Intensity Measure Relationship (IMR), Earthquake Rupture Forecast (ERF), and site. Type: Tool
Hazard Modeller's Toolkit	GEM	OpenQuake - GEM	Yes	A suite of tools used to create probabilistic seismic hazard analysis (PSHA) input models. Type: Suite of tools
HAZUS	Federal Emergency Management Agency (FEMA)	FEMA	Yes	A standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes using data from geographical information systems (GIS). Hazus is often used in the mitigation planning process and estimates physical damage, economic loss, and social impacts. Type: Model

Program	Developed by	Available from	Public Domain?	Description
Open Seismic Hazard Analysis (OpenSHA)	University of Southern California	OpenSHA and the University of Southern California	Freeware	A java-based, open-source platform to develop seismic hazard [illegible] models. The models below we[illegible] OpenSHA. Type: Model
Risk Modeler's Toolkit	GEM	OpenQuake - GEM	Freeware	A suite of tools used t[illegible]sure, fragility, and vulnerability [illegible] models. Type: Suite of tools
Risk-Targeted Ground Motion Calculator	USGS	USGS - Earthquake Hazards Program	Yes	A web tool used to calculate risk-targeted ground motion values. The output is the risk-targeted ground motion corresponding to a 1% probability of collapse in 50 years. This value can be used for seismic design of buildings. Type: Web tool
ShakeMap	USGS	USGS - Earthquake Hazards Program	Yes	A program that has real-time, historic, and scenario earthquake maps that display color-coded areas of ground shaking intensity, as well as peak ground acceleration, velocity amplitudes etc. The program allows the user to generate hypothetical scenarios and analyze the associated data. Type: Tool

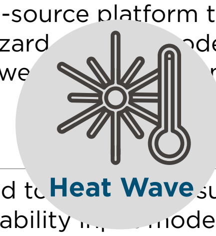


Table AD.4. Heat Wave Models

Program	Developed by	Available from	Public Domain?	Description
Artificial Intelligence Fuzzy Logic Model	Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing	National Observatory of Athens	Yes	Model to classify the heat waves from mild to extreme by taking into consideration their duration, intensity and time of occurrence. Type: Model

Program	Developed by	Available from	Public Domain?	Description
Heat Wave Magnitude Index (HWMI) with Coupled Model Intercomparison Project Phase 5 (CMIP5)	European Commission, Joint Research Centre, Ispra, Italy; Institute for Environmental Protection and Research, Rome, Italy	1) HWMI: European Commission, Joint Research Centre, Institute for Environmental Protection and Research 2) CMIP5: World Climate Research Programme	Yes	The HWMI is based on a maximum temperature gest heave waves worl compared over space a from the CMPI5 Phase 5 project future occurrence ty of heatwaves. Type: Model
Heat Wave Risk (HWR) through ArcGIS	National Aeronautics and Space Administration (NASA)	NASA	Yes	HWR produced from climatological weather station data, moderate resolution thermal imagery, and demographic information. Type: Model
High Resolution Atmospheric Model (HiRAM)	National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory	NOAA	Yes	HiRAM was developed with a goal of providing an improved representation of significant weather events in a global climate model and has been used to study historic and future simulated heat waves. Type: Model
Spatial heat wave methodology using EatlasClimMod 1.0 application	Ibn Zohr University of Morocco and Vulnerability and Risk Analysis Mapping program	1) Methodology: Ibn Zohn University of Agadir, Morocco 2) EatlasClimMod 1.0: World Health Organization	Yes	A methodology used to spatially distribute heat wave hazard. EatlasClimMod 1.0 is a module to calculate different climatic variables used to spatially distribute several hazards. Type: Model

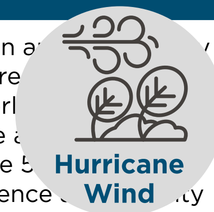


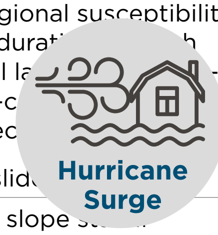
Table AD.5. Hurricane Wind Models

Program	Developed by	Available from	Public Domain?	Description
HAZUS	Federal Emergency Management Agency (FEMA)	FEMA	Yes	A standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricane winds and storm surge using data from geographical information systems (GIS). Hazus is often used in the mitigation planning process and estimates physical damage, economic loss, and social impacts.
ERN-HURRICANE (ERN-Huracán)	Central American Probabilistic Risk Assessment Platform (CAPRA)	CAPRA	Yes	ERN-Hurricane is a hurricane threat probabilistic modeling system, developed by ERN-AL. The program takes as input the recorded paths of historic hurricanes and generates stochastic paths that are consistent with the original path. It calculates threat scenarios by high winds, storm surge and heavy rain.
Inland Wind Decay Model (IWDM)	Mark DeMaria NOAA/NWS/ TPC and John Kaplan NOAA/ AOML/ HRD	National Oceanic and Atmospheric Administration	No	Empirical model for predicting the decay of hurricane winds after landfall. The model applies a simple two-parameter decay equation to the hurricane wind field at landfall to estimate the maximum sustained surface wind as a storm moves inland. Used to estimate maximum inland penetration of hurricane force winds for a given storm intensity and storm motion.

Table AD.6. Landslide Models

Program	Developed by	Available from	Public Domain?	Description
Energy Cone	Universidad de Concepción, Chile	Volcano Hub (VHub)	Freeware	A tool to estimate the runout and inundation area of landslides and other mass movements using digital elevation models (DEM). The output is an energy cone contour on top of a hillshade image. Type: Tool

Program	Developed by	Available from	Public Domain?	Description
LandLab	University of Colorado, Boulder	Land Lab	Yes	A python-based modeling environment that allows users to create numerical landscape models to quantify earth surface dynamics. The LandLab landslide component computes flow of landslide debris and can access geographical data from ArcGIS. Probability of failure is generated through factor of safety calculations. Type: Python-based toolkit
Landslide Hazard Assessment for Situational Awareness (LHASA)	National Aeronautics and Space Administration (NASA)	NASA	Yes	LHASA considers both regional susceptibility and rainfall intensity and durat h the integration of regional la -tibility maps and satellite-c estimates into a binary dec Type: Tool to assess landslid
Scoops3D/ Scoops3Di (April 2015)	U.S. Geological Survey (USGS)	USGS, Landslide Hazards Program	Yes	A program that evaluates slope st ty based on a DEM of the landscape. The results represent a combination of the least-stable potential slope failures in a landscape. Results can be incorporated into a geographic information system. Type: Scoops3D is an assessment program. Scoops3Di is the component of the Scooops3D program.
Seismic Landslide Movement Modeled using Earthquake Records (SLAMMER) (November 2014)	USGS	USGS, Techniques and Methods	Yes	A Java-based program that facilitates a sliding-block analysis of slopes to estimate slope behavior during earthquakes. Type: Analysis program.
Stability Index Mapping (SINMAP 2.0) (June 2007)	Utah State University and Terratech Consulting	Utah State University, Department of Civil and Environmental Engineering	Freeware	An ArcMap add-in used to compute and map a slope stability index based on geographic information, primarily DEM. Parameters, such as soil, vegetation, and geologic data, may be adjusted and calibrated for different geographic regions. Type: Tool add-in for ArcMap
Titan2D Hazard Map Emulator Workflow	University at Buffalo, NY	Volcano Hub (VHub)	Freeware	A tool that works with Titan2D to produce hazard maps that display the probability of flow depth reaching a critical height. Type: Tool component of Titan2D Mass-Flow Simulation tool
Titan2D Mass-Flow Simulation Tool (June 2016)	University at Buffalo, NY	Volcano Hub (VHub)	Freeware	A model that determines mass flow over natural terrain, e.g. volcanic flows and debris landslides, using a digital elevation model data. Designed to be used with geographical information systems like ArcGIS and GRASS. Type: Model toolkit



Program	Developed by	Available from	Public Domain?	Description
Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model	USGS	USGS, Landslide Hazards Program	Yes	A Fortran program designed to model the timing and distribution of shallow, rainfall-induced landslides. This program is used in conjunction with GIS software to prepare input grids and visually present model results. Type: Fortran program model

Table AD.7. Riverine Flood Models

Program	Developed by	Available from	Public Domain?	Description
		Single Event		
Gridded Surface Subsurface Hydrologic Analysis (GSSHA) Version 1.43 and up (Sept. 2006)	U.S. Army Corps of Engineers (USACE)	U.S. Army Engineering Research and Development Center, Coastal and Hydraulics Laboratory	Yes	GSSHA is a spatially explicit, physics-based hydrologic model that can simulate a wide range of runoff mechanisms, including infiltration-excess and saturation-excess runoff, snow melt, storm and tile drains, groundwater exfiltration and discharge, lakes (including non-draining lakes such as prairie potholes), detention basins, culverts and weirs. GSSHA is suitable in many coastal watershed applications and has been applied from jungle rainforests to urban storm surge flooding simulations in New Orleans and New York City. Type: Model supported by Watershed Modeling System
HEC-1 4.0.1 and up[1] (May 1991)	USACE	Water Resources Support Center Corps of Engineers Hydrologic Engineering Center	Yes	Hydrologic Engineering Center (HEC)-1 is a hydrograph package that creates flood hydrographs at different locations along streams. Calibration runs preferred to determine model parameters. Type: Model software [1] The enhancement of the program in editing and graphical presentation can be obtained from several private companies.
HEC-HMS 1.1 and up (Mar 1998)	USACE	USACE Hydrologic Engineering Center	Yes	The HEC Hydrologic Modeling System (HMS) simulates the complete hydrologic processes of dendritic watershed systems. HEC-HMS provides a variety of options for simulating precipitation-runoff processes, including snowmelt and interior pond capabilities, plus enhanced reservoir options. Type: Model software

Program	Developed by	Available from	Public Domain?	Description
MIKE 11 (2009 SP4)	DHI Water and Environment	DHI, Inc.	No	MIKE 11 simulates flood hydrographs at different locations along streams using unit hydrograph techniques. Three methods are available for calculating infiltration losses and three methods for converting rainfall excess to runoff, including SCS Unit hydrograph method. Type: Model package. MIKE HYDRO River is successor of MIKE 11. It includes map-based interface for river modeling
FLDWAV	National Weather Service (NWS)	NWS		FLDWAV is a generalized flood routing program with the capability to model flood flows through a single stream or a system of interconnected waterways and includes all the features of DAMBRK and DWOPER plus additional capabilities. It is a computer program for the solution of the fully dynamic equations of motion for one-dimensional flow in open channels and control structures. Floodway concept formulation is unavailable. Type: Model
PondPack v.8 (May 2002) and up	Bentley Systems	Bentley Systems	No	The program analyzes watershed networks by modeling rainfall and runoff from urban and rural watersheds to aid in sizing detention or retention ponds, outlet structures, and channels. Type: Model
SWMM 5 Version 5.0.005 (May 2005) and up	U.S. Environmental Protection Agency (EPA)	EPA Water Supply and Water Resources Division	Yes	Storm Water Management Model (SWMM) 5 is a dynamic hydrology-hydraulic water quality model used for single event or long-term simulations for primarily urban areas. The runoff component operates on sub-catchment areas that receive rainfall and generate runoff and pollutant loads. The routing component consists of pipes, channels, storage/treatment devices, pumps and regulators. Type: Model
TR-20 Win 1.00 (Jan 2005)	U.S. Department of Agriculture (USDA), Natural Resources Conservation Service	USDA, Natural Resources Conservation Service	Yes	The TR-20 computer model has been revised and completely rewritten as a Windows-based program. It is a storm event surface water hydrologic model applied at a watershed scale that can generate, route and combine hydrographs at points within a watershed. Type: Model

Program	Developed by	Available from	Public Domain?	Description
WinTR-55 1.0.08 (Jan 2005)	USDA, Natural Resources Conservation Service	USDA, Natural Resources Conservation Service	Yes	The new WinTR-55 uses the WinTR-20 program as the driving engine to analyze the hydrology of small watershed systems. Type: Model
XPSTORM 10.0 (May 2006)	XP Solutions	XP Solutions		Xpstorm is a program that models stormwater and wastewater flows and pollutants through engineered systems and natural systems, including rivers, lakes, and floodplains, with groundwater interaction. Simulations can be used to evaluate the performance of engineered systems. Type: Model
XP-SWMM 8.52 and up	XP Solutions	XP Solutions	No	XPSWMM has the same modeling capability as XPSTORM and they are often used in conjunction and referred to collectively as XP. Model must be calibrated to observed flows, or discharge per unit area must be shown to be reasonable in comparison to nearby gage data, regression equations or other accepted standards for 1% annual chance events. Type: Model
Continuous simulation				

Program	Developed by	Available from	Public Domain?	Description
Gridded Surface Subsurface Hydrologic Analysis (GSSHA) Version 1.43 and up (Sept. 2006)	USACE	U.S. Army Engineering Research and Development Center, Coastal and Hydraulics Laboratory	Yes	GSSHA is a spatially explicit, physics-based hydrologic model that can simulate a wide range of runoff mechanisms, including infiltration-excess and saturation-excess runoff, snow melt, storm and tile drains, groundwater exfiltration and discharge, lakes (including non-draining lakes such as prairie potholes), detention basins, culverts and weirs. GSSHA is suitable in many coastal watershed applications and has been applied from jungle rainforests to urban storm surge flooding simulations in New Orleans and New York City. Type: Model supported by Watershed Modeling System
HEC-HMS 3.0 and up (Dec 2005)	USACE	USACE Hydrologic Engineering Center	Yes	The HEC-Hydrologic Modeling System (HMS) simulates the complete hydrologic processes of dendritic watershed systems. HEC-HMS 3.0 and up include two different soil moisture models suitable for continuous modeling, one with five layers and one with a single layer. Two approaches to evapotranspiration are provided and snowmelt is available. Type: Model software
HSPF 10.10 and up (Dec 1993)	U.S. Environmental Protection Agency, U.S. Geological Survey	U.S. Environmental Protection Agency	Yes	Hydrological Simulation Program-Fortran (HSPF) is used for simulating watershed hydrology and water quality for both conventional and toxic organic pollutants. The result of this simulation is a time history of runoff flow rate, sediment load, and nutrient and pesticide concentrations, in addition to time history of water quantity and quality at any point in the watershed. Type: Fortran program Model

Program	Developed by	Available from	Public Domain?	Description
MIKE 11 RR (2009 SP4)	DHI Water and Environment	DHI, Inc.	No	MIKE 11 is a rainfall-runoff module lumped-parameter hydrologic model capable of continuously accounting for water storage in surface and sub-surface zones. Flood hydrographs are estimated at different locations along streams. Calibration to actual flood events is required. Type: Model package. MIKE HYDRO River is the successor of MIKE 11. Includes map-based interface for river modeling.
PRMS Version 2.1 (Jan 1996)	U.S. Geological Survey (USGS)	USGS, Watershed Modeling	Yes	Precipitation Runoff Modeling System (PRMS) is a modular-designed, deterministic, distributed-parameter modeling system that can be used to estimate flood peaks and volumes for floodplain mapping studies. PRMS is also used to evaluate the response of various combinations of climate and land use streamflow and general watershed hydrology. The program can be implemented within the Modular Modeling System that facilitates the user interface with PRMS, input and output of data, graphical display of the data and an interface with GIS. Type: Model incorporated into Modular Modeling System
		Statistical models		
FAN	Federal Emergency Management Agency (FEMA)	FEMA	Yes	FAN, FEMA's Alluvial Fan Flooding software, is used to define special flood hazard information in areas subject to alluvial fan flooding. The model does not define the extent of the special flood hazard area (SFHA); rather, it develops output information that can, in conjunction with soil, topographic, and geomorphic information, be used to divide the SFHA into zones of similar depth and velocity. The minimum input required is the flood-frequency relation at the apex. Options allow for consideration of multiple flow paths with or without avulsions during flood events. Type: Model
HEC-SSP 1.1 (April 2009) and up	USACE	Water Resources Support Center 1 Corps of Engineers Hydrologic Engineering Center	Yes	HEC Statistical Software Package (SSP) allows users to perform statistical analyses of hydrologic data including flood frequency and volume frequency, duration, coincident frequency, and balanced hydrograph analyses. Type: Analysis tool

Program	Developed by	Available from	Public Domain?	Description
PEAKFQ 2.4 (April 1998) and up	USGS	USGS, Water Resources	Yes	PeakFQ provides estimates on flood magnitudes and their corresponding variance for a range of 15 annual exceedance probabilities. PKFQWin is the Windows version of the PEAKFQ program. Type: Analysis tool
		One-dimensional steady flow hydraulic models		
cHECk-RAS	FEMA	FEMA		cHECk-RAS is a program designed to verify the validity of an assortment of parameters found in the U. S. Army Corps of Engineers HEC-RAS hydraulic modeling program. cHECk-RAS utilizes information generated by HEC-RAS (all versions through the latest version, 4.1.0.) This program can run only on computers with Microsoft Windows XP, Vista, or 7 (32- or 64-bit) operating systems. Type: Validation tool for HEC-RAS model program
Culvert Master v. 2.0 (September 2000), and up	Bentley Systems	Bentley Systems	No	Culvert Master computes headwater elevations for circular concrete and RCB culverts for various flow conditions. Type: Tool to analyze existing and new culverts.
HEC-2 4.6.2 [1] (May 1991)	USACE	Water Resources Support Center Corps of Engineers Hydrologic Engineering Center 609 Second Street Davis, CA 95616-4687	Yes	HEC-2 calculates water surface profiles for steady gradually varied flow in natural or man-made channels. The program can model the effect of bridges, culverts, and weirs. The model includes culvert analysis and floodway options. Type: Model
HEC-RAS 3.1.1 and up	USACE	Water Resources Support Center Corps of Engineers Hydrologic Engineering Center	Yes	HEC-River Analysis System (RAS) allows the user to model water surface elevation difference due to use of different HEC-RAS versions. Version 3.1 cannot create detailed output for multiple profiles in the report file. CHECK-RAS cannot extract data. Type: Model
HY8 4.1 and up (Nov. 1992)	U.S. Department of Transportation, Federal Highway Administration (FHA)	FHA	Yes	The model computes water-surface elevations for flow through multiple parallel culverts and over the road embankment. Type: Model

Program	Developed by	Available from	Public Domain?	Description
PondPack v. 8 (May 2002) and up	Bentley Systems	Bentley Systems	No	The program analyzes watershed networks by modeling rainfall and runoff from urban and rural watersheds to aid in sizing detention or retention ponds, outlet structures, and channels. Cannot model ineffective flow areas. HEC-RAS or an equivalent program must be used to model tail water conditions when ineffective flow areas must be considered. Type: Model
XXXQUICK-2 1.0 and up (Jan. 1995)	FEMA	FEMA Federal Insurance and Mitigation Administration	Yes	QUICK-2 is a hydraulic analysis program used to compute water surface elevations in open channels. Intended for use in areas studied by approximate methods (Zone A) only. May be used to develop water-surface elevations at one cross section or a series of cross sections. May not be used to develop a floodway. Type: Model
RASPLOT 3.0 Beta	FEMA	FEMA Federal Insurance and Mitigation Administration	Yes	RASPLOT is a computer program developed by FEMA which allows the user to create flood profiles through the automatic extraction of data from HEC-RAS hydraulic modeling files. Flood profiles are required for inclusion in the Flood Insurance Study (FIS) reports which usually accompany the Flood Insurance Rate Map (FIRM) for communities participating in FEMA's National Flood Insurance Program. Type: Tool using extracted data from HEC-RAS
StormCAD v.4 (June 2002) and up	Bentley Systems	Bentley Systems	No	StormCAD is a storm sewer design and analysis program that uses runoff flow and precipitation data to help determine cost-effective pipe sizes and invert elevations. Should not be used for systems with more than two steep pipes (e.g. supercritical conditions). Inflow is computed by using the Rational Method; the program is only applicable to watersheds where the drainage area to each inlet is less than 300 acres. Type: Analysis and design tool
WSPGW 12.96 (Oct. 2000) and up	Los Angeles Flood Control District and Joseph E. Bonadiman & Associates, Inc.	Joseph E. Bonadiman & Associates, Inc.	No	Windows version of Water Surface Pressure Gradient (WSPG). WSPG is a hydraulic analysis model that computes and plots water-surface profiles and pressure gradients for open channels and closed conduits. Type: Model

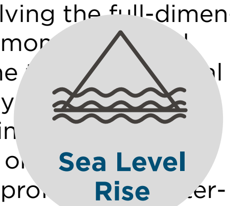
Program	Developed by	Available from	Public Domain?	Description
WSPRO (Jun. 1988 and up)	USGS, FHA	USGS	Yes	WSPRO computes water-surface profiles and is used to analyze open channel flow, flow through bridges, flow through culverts, embankment overflow and multiple-opening stream crossings. Floodway option is available in June 1998 version. Type: Model
XPSTORM 10.0 (May 2006)	XP Solutions	XP Solutions	No	Xpstorm is a program that models stormwater and wastewater flows and pollutants through engineered systems and natural systems including rivers, lakes, and floodplains with groundwater interaction. Simulations can be used to evaluate the performance of engineered systems. Type: Model
XP-SWMM 8.52 and up	XP Solutions	XP Solutions	No	XP-SWMM has the same modeling capability as XPSTORM and they are often used in conjunction and referred to collectively as XP. Model must be calibrated to observed flows, or discharge per unit area must be shown to be reasonable in comparison to nearby gage data, regression equations or other accepted standards for 1% annual chance events. Type: Model
One-dimensional unsteady flow hydraulic models				
FEQ 9.98 and FEQUTL 5.46 (2005, both), and up	Delbert D. Franz, Linsley, Kraeger Associates; and Charles S. Melching, U.S. Geological Survey (USGS)	USGS	Yes	The FEQ model is a computer program for the solution of full, dynamic equations of motion for one-dimensional unsteady flow in open channels and control structures. The hydraulic characteristics for the floodplain (including the channel, overbanks, and all control structures affecting the movement of flow) are computed by its companion program FEQUTL and used by the FEQ program. Floodway concept formulation is unavailable. Type: Model

Program	Developed by	Available from	Public Domain?	Description
FLDWAV (Nov. 1998)	National Weather Service (NWS)	NWS	Yes	FLDWAV is a generalized flood routing program with the capability to model flood flows through a single stream or a system of interconnected waterways and includes all the features of DAMBRK and DWOPER plus additional capabilities. It is a computer program for the solution of the fully dynamic equations of motion for one-dimensional flow in open channels and control structures. Floodway concept formulation is unavailable. This model has the capability to model sediment transport. Type: Model
FLO-2D v. 2007.06 and 2009.06	Jimmy S. O'Brien	FLO-2D	No	FLO-2D is a hydrodynamic model that has the capability to model unconfined flows, complex channels, sediment transport, and mud and debris flows. Type: Model
HEC-RAS 3.1.1 and up	USACE	Water Resources Support Center USACE Hydrologic Engineering Center	Yes	HEC-River Analysis System (RAS) allows the user to model water surface elevation difference due to use of different HEC-RAS versions. Version 3.1 cannot create detailed output for multiple profiles in the report file. CHECK-RAS cannot extract data. Type: Model
ICPR 2.20 (Oct. 2000), 3.02 (Nov. 2002), and 3.10 (April 2008) with PercPack Option	Streamline Technologies, Inc.	Streamline Technologies, Inc.	No	The model must be calibrated to observed flow and stage records or high-water marks of actual flood events at both channel and floodplain. Floodway concept formulation unavailable; however, version 3 allows users to specify encroachment stations to cut off the cross section. Type: Model
MIKE 11 HD v.2009 SP4	DHI Water and Environment	DHI, Inc.	No	MIKE 11 is a hydrodynamic model for the solution of the fully dynamic equations of motion for one- dimensional flow in open channels and control structures. The floodplain can be modeled separately from the main channel. Floodway concept formulation is available for steady flow conditions. This model has the capability to model sediment transport. Type: Model

Program	Developed by	Available from	Public Domain?	Description
SWMM 5 Version 5.0.005 (May 2005) and up	U.S. Environmental Protection Agency	Water Supply and Water Resources Division	Yes	Storm Water Management Model (SWMM) 5 is a dynamic hydrology-hydraulic water quality model used for single-event or long-term simulations for primarily urban areas. The runoff component operates on sub-catchment areas that receive rainfall and generate runoff and pollutant loads. The routing component consists of pipes, channels, storage/treatment devices, pumps and regulators. Type: Model
HEC-UNET 4.0 (April 2001)	USACE	Water Resources Support Center Corps of Engineers Hydrologic Engineering Center	Yes	HEC-UNET is a one-dimensional unsteady flow program that can simulate flow in a full network of open channels. Type: Model
Xpstorm 10.0 (May 2006)	XP Solutions	XP Solutions	No	Xpstorm is a program that models stormwater and wastewater flows and pollutants through engineered systems and natural systems including rivers, lakes, and floodplains with groundwater interaction. Simulations can be used to evaluate the performance of engineered systems. Type: Model
XP-SWMM 8.52 and up	XP Solutions	XP Solutions	No	XPSWMM has the same modeling capability as XPSTORM and they are often used in conjunction and referred to collectively as XP. Model must be calibrated to observed flows, or discharge per unit area must be shown to be reasonable in comparison to nearby gage data, regression equations or other accepted standards for 1% annual chance events. Type: Model
Two-dimensional steady/unsteady flow models				
Adaptive Hydraulics (AdH) version 4.2 and up (June 2012)	USACE	USACE Research and Development Center Coastal and Hydraulics Laboratory	Yes	AdH is a spatially implicit, physics-based hydrodynamic model that can simulate a wide range of hydraulic features, including rainfall and evaporation, overland flooding, wind and wave effects, friction impacts due to vegetation, and several types of hydraulic structures. AdH also includes the ability to simulate time and space varying head and flow boundary conditions, making it suitable in many coastal, estuarine, and riverine applications. AdH has been applied in the high tidal ranges of Alaska and in the deserts of Afghanistan. AdH has been used widely throughout the U.S. for sediment and constituent transport, dam break, tidal impacts, and flooding analyses. Type: Model

Program	Developed by	Available from	Public Domain?	Description
FESWMS 2DH 1.1 and up (Jun. 1995)	USGS	USGS National Center	Yes	FESWMS-2DH is a modular set of computer programs that simulates surface water flows and sediment transport. The program can analyze flow in shallow rivers, flood plains, estuaries, coastal seas and at bridge crossings. Type: Set of computer programs.
FLO-2D v. 2007.06 and 2009.06	Jimmy S. O'Brien	FLO-2D	No	FLO-2D is a hydrodynamic model that has the capability to mode unconfined flows, complex channels, sediment transport, and mud and debris flows. Type: Model
HEC-RAS Version 5.0	USACE	Water Resources Support Center USACE Hydrologic Engineering Center	Yes	HEC-RAS models water surface elevation. Version 5.0 has the ability to perform two-dimensional (2D) hydrodynamic routing within the unsteady flow analysis portion of HEC-RAS. Users can perform one-dimensional (1D) unsteady-flow modeling, two-dimensional (2D) unsteady-flow modeling, as well as combined 1D and 2D unsteady-flow routing Type: Model
MIKE Flood HD v.2009 SP4	DHI Water and Environment	DHisoftware.com/	No	MIKE FLOOD HD is a dynamic coupling of MIKE 11 (one-dimensional) and MIKE 21 (two-dimensional) models. Solves the fully dynamic equations of motion for one- and two-dimensional flow in open channels, riverine flood plains, alluvial fans and costal zones. This allows for embedding of subgrid features as 1-D links within a 2D modeling domain. Examples of sub-grid features could include small channels, culverts, weirs, gates, bridges, and other control structures. Type: Model
Sedimentation and River Hydraulics, Two-Dimensional River Flow Model (SRH-2D)	U.S. Bureau of Reclamation Technical Service Center Sedimentation and River Hydraulics Group Denver Federal Center 6th and Kipling, Building 67 Denver, CO 80225-0007	U.S. Department of Transportation FHA	Yes	SRH-2D, Sedimentation and River Hydraulics – Two-Dimensional model, is a two-dimensional (2D) hydraulic, sediment, temperature, and vegetation model for river systems. SRH-2D is used to model Flow in one or multiple streams covering the main channel, side channels, and floodplains, flood routing and inundation mapping over any terrain, flow around in-stream structures such as weirs, diversion dams, release gates, coffer dams, etc., flow over-spill over banks and levees, flow over vegetated areas and interaction with main channel flows, flow in reservoirs with known flow release, and morphological assessment of bed erosion potential. Type: Model

Program	Developed by	Available from	Public Domain?	Description
TABS RMA2 v. 4.3 and up (Oct. 1996) RMA4 v. 4.5 and up (July 2000)	USACE	Coastal Engineering Research Center Department of the Army Waterways Experiment Station Corps of Engineers	Yes	TABS RMA2 v 4.3 is a two-dimensional steady/unsteady flow model that simulates water levels and velocities. The model computes finite element solutions of the Reynolds form of the Navier-Stokes equations for turbulent flows. Type: Modeling code component of TABS analysis package.
XPSWMM 2D/ XPStorm 2D v. 12.00 (May 2010)	XP Solutions	XP Solutions	No	The program simulates two-dimensional free surface flows by solving the full-dimensional, depth averaged, mom[illegible] continuity equations. The [illegible] simulation is dynamically [illegible] one-dimensional modelin[illegible] XP-Storm by taking the o[illegible] water surface elevation pro[illegible] [illegible]ter-nal boundary condition of the 2D domain. Flow rates transferred depend upon the head difference and the roughness of cells. The program does not have any option to model weir flow along 1D/2D boundary; caution must be exercised when transferring flow along these boundaries. Type: Model
HydroBID	Inter-American Development Bank (IDB)	IDB HydroBID	Yes	An integrated and quantitative system to simulate hydrology and water resource management in the Latin America and the Caribbean region under scenarios of change (e.g., climate, land use, population) which allows to evaluate the quantity and quality of water, infrastructure needs, and the design of strategies and adaptive projects in response to these changes. Type: Model
ERN-NHRAIN (ERN-LluviaNH)	Central American Probabilistic Risk Assessment Platform (CAPRA)	CAPRA)	Yes	This software allows the generation of elliptical stochastic storms that are obtained from PADF (precipitation, area, duration, frequency) curves for a given basin. The modeling of rainfall not associated with the passing of a hurricane nearby a specific region can be performed using ERN-LluviaNH, developed by ERN-AL. Type: Model
ERN-HURRICANE (ERN-Huracán)	CAPRA	CAPRA	Yes	ERN-Hurricane is a probabilistic hurricane threat modeling system developed by ERN-AL. The program takes as input the recorded paths of historic hurricanes and generates stochastic paths that are consistent with the original path. Calculates threat scenarios by high winds, storm surge and heavy rain. Type: Model



Program	Developed by	Available from	Public Domain?	Description
ERN-FLOOD (ERN-Inundación)	CAPRA	(CAPRA)	Yes	ERN-Inundación allows the analysis of river flooding, based on a set of stochastic rainfall scenarios calculated with ERN-Huracán (for hurricane rain) or ERN-LluviaNH (for non-hurricane rain). Type: Model

Table AD.8. Sea Level Rise Models

Program	Developed by	Available from	Public Domain?	Description
Sea Level Rise Inundation with ArcGIS	Office for Coastal Management, National Oceanic and Atmospheric Administration (NOAA)	NOAA	Software: No Method: Yes	Methodology for generating sea level rise inundation for the Sea Level Rise Viewer. Method is described as a modified bathtub approach that attempts to account for local and regional tidal variability and hydrological connectivity.
Probabilistic Sea-Level Rise Hazard Analysis (PSLRHA)	Ting Lin, Civil and Environmental Engineering, Stanford University	Ting Lin, Civil and Environmental Engineering, Stanford University, Email: tinglin@stanford.edu	Yes	Framework integrates sea-lev [illegible] edge of current climate cha [illegible] communities for informed [illegible] policy decisions that affect [illegible] structure, populations, and e [illegible] LRHA combines probabilities [illegible] scenarios with predictions of the resulting sea-level rise over time, in order to compute sea-level rise hazard.
Potential Inundated Areas using GIS	Xingong Li and David Braaten, University of Kansas, and Center for Remote Sensing of Ice Sheets (CReSIS)	Xingong Li and David Braaten, University of Kansas and CReSIS	No	GIS methods to address and visualize the impacts of potential inundation using best available global datasets. Estimations of area size, population, and land cover were addressed for all increments of sea level rise.
CoastCLIM Sea-Level Simulator (component of SimCLIM system)	CLIMsystems	CLIMsystems	No	Database tool for generating predicted sea-level curves for any global coastal location. Uses a global database of regional grid cells to generate localized rates of sea-level change associated with downscaled GCM projections of future sea-level rise and CO2 emission scenarios. A total of six emission scenarios are included.

Program	Developed by	Available from	Public Domain?	Description
Inundation Frequency Analysis Program	National Oceanic and Atmospheric Administration (NOAA) National Ocean Services	NOAA National Ocean Services	Yes	The program uses observed 6-min water-level records of tide gages relating observed times and heights of high-water tides for a desired period of record as data input. Output is an Excel spreadsheet that takes each high tide in specified time period relative to the user-specified reference datum. Inundation analysis generates graphs of occurrences by elevation and duration.
ArcGIS	Environmental Systems Research Institute (ESRI)	ESRI	No	ArcGIS provides contextual tools for mapping and spatial reasoning to explore data and share information. Among other areas, the program is used to generate sea level rise inundation maps through several toolsets including, but not limited to, Spatial Analyst.

Table AD.9. Tsunami Models

Program	Developed by	Available from	Public Domain?	Description
MOST Model (Method of Splitting Tsunami)	Pacific Marine Environmental Laboratory (PMEL) and National Oceanic and Atmospheric Administration	PMEL	Yes	MOST model proceeds in 3 stages: 1) Deformation phase generates initial conditions by simulating ocean floor changes from seismic event; 2) Propagation phase propagates generated tsunami across deep ocean using Nonlinear Shallow Water wave equations; 3) Inundation phase simulates shallow ocean behavior using multi-grid run-up to predict coastal flooding and inundation.
ADCIRC (Advanced Circulation Model)	Johannes Westerink, University of Notre Dame and Rick Luettich, University of North Carolina at Chapel Hill, Institute of Marine Sciences for USACE Coastal and Hydraulics Laboratory	Nick Krauss (Coastal and Hydraulics Laboratory) 3909 Halls Ferry Road Vicksburg, MS 39180-6199. Also can be purchased from software vendors as a component of SWM.	No	ADCIRC is a finite element 2-D hydrodynamic model that performs analyses through short- and long-term simulations of tide and storm surge elevations and velocities in deep-ocean, continental shelves, coastal seas, and small-scale estuarine system.
TUNAMI-N1	Tohoku University, Japan	Disaster Control Research Center, Tohoku University, Sendai, Japan	No	Numerical method of tsunami simulation with leap-frog scheme. N1 code consists of a linear theory with constant grids.

Program	Developed by	Available from	Public Domain?	Description
TUNAMI-N2	Tohoku University, Japan	Disaster Control Research Center, Tohoku University, Sendai, Japan	No	Numerical method of tsunami simulation with leap-frog scheme. N2 code consists of a linear theory in deep sea, shallow-water theory in shallow sea and runup on land with constant grids.
TUNAMI-N3	Tohoku University, Japan	Disaster Control Research Center, Tohoku University, Sendai, Japan	No	Numerical method of tsunami simulation with leap-frog scheme. N3 code consists of a linear theory with varying grids.
TUNAMI-F1	Tohoku University, Japan	Disaster Control Research Center, Tohoku University, Sendai, Japan	No	Numerical method of tsunami simulation with leap-frog scheme. F1 code consists of a linear theory for propagation in the ocean in the spherical coordinates.
TUNAMI-F2	Tohoku University, Japan	Disaster Control Research Center, Tohoku University, Sendai, Japan	No	Numerical method of tsunami simulation with leap-frog scheme. F2 code consists of a linear theory for propagation in the ocean and coastal waters.
TsunAWI	Alfred Wegener Institute	Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany	No	Based on unstructured finite element meshes, utilizing a linear Lagrange conforming and non-conforming finite element numerical discretization method. TsunAWI is used for scenario computations in the German-Indonesian Tsunami Early Warning System (GITEWS) as well as in Indonesia.
COULWAVE (Cornell University Long and Intermediate Wave Modeling Package)	Initial development by Patrick Lynett under Philip Liu at Cornell University, 2000. Additional development by Lynett at Texas A&M University, 2002 - plynett@tamu.edu	Inundation Science and Engineering Cooperative	Yes	Surface wave model that solves various depth-integrated, long-wave based equation models, including nonlinear shallow water wave equations and a number of the weakly dispersive Boussinesq-type equations.
DELFT3D FM	Deltares	Rotterdamseweg 185,2629 HD, Delft, The Netherlands XP PO Box: P.O. Box 177, 2600 MH Delft, The Netherlands	No	This model is the next generation of DELFT3D hydrodynamical simulations module on unstructured grids in 1D-2D-3D. DELFT3D FM simulates storm surges, hurricanes, tsunamis, detailed flows and water levels, waves, sediment transport and morphology, and water quality and ecology.

Table AD.10. Volcano Models

Program	Developed by	Available from	Public Domain?	Description
Bent – Atmospheric Plume Analysis	University at Buffalo, SUNY	Volcano Hub (VHub)	Freeware	A theoretical model of a volcanic plume, based on applying the equations of motion in a plume-centered coordinate system. Type: Model
CAPRA-GIS	Central American Probabilistic Risk Assessment Platform (CAPRA)	CAPRA	Yes	A geographic information system (GIS)-based tool that uses a probabilistic approach to generate distributions of disaster risk and impacts based on vulnerability and exposure to various hazards. Type: Tool.
Energy Cone	Universidad de Concepcion, Chile	Volcano Hub (VHub)	Yes	A tool to estimate the runout and inundation area of landslides and other mass movements using digital elevation models (DEM). The output is an energy cone contour on top of a hillshade image. Type: Tool
ERN-Volcano	CAPRA	CAPRA	Yes	A program that integrates all the variables included in the model for volcanic hazard assessment of CAPRA-GIS and generates scenarios that represent the threat provided by the volcano analysis. Type: Model
Laharz_py	U.S. Geological Survey (USGS)	USGS	Yes	A python-based suite of tools to be used in ArcMap which forecasts areas likely to be inundated by hypothetical future events using 3D DEM and user-specified levels of confidence. The res[illegible] can be displayed on maps that c[illegible] range of inundation area. Type: Tool for ArcMap.
Puffin/Puff	University at Buffalo, NY	Volcano Hub (VHub)	Yes	A tool to run the volcanic [illegible] model – puff – based on the [illegible]c-tory model – bent. Type: Puffin is a tool to run "Puff" model based on "Bent" Model.
PyBetUnrestPy-BedUnrest	Instituto Nazionale di Geofisica e Vulcanologia di Roma and Bologna, Italy	Volcano Hub (VHub)	Freeware	A tool to compute and visualize short- and long-term volcanic hazard associated with magmatic and non-magmatic unrest using a Bayesian Event Tree (BET) model. Type: Component of BET_UNREST Model

Program	Developed by	Available from	Public Domain?	Description
PyBetVH (Jan 2016)	Instituto Nazionale di Geofisica e Vulcanologia di Bologna, Italy	Volcano Hub (VHub)	Freeware	A tool to compute long-term volcanic hazard using the Bayesian Event Tree (BET) for volcanic hazard model. Type: Component of BET_VH model. A program that computes long-term probability of volcanic hazardous phenomena, e.g. lava flows, tephra fall, pyroclastic flows, lahars, etc.
Tephra2	University of Geneva, Switzerland and University of South Florida	Volcano Hub (VHub)	Yes	Uses advection diffusion equation to forecast tephra dispersion in a given location based on a user-defined set of eruptive conditions. Type: Tool
Titan2D Hazard Map Emulator Workflow	University at Buffalo, NY	Volcano Hub (VHub)	Yes	A tool that works with Titan2D to produce hazard maps that display the probability of flow depth reaching a critical height. Type: Tool component of Titan2D Mass-Flow Simulation tool
Titan2D Mass-Flow Simulation Tool (June 2016)	University at Buffalo, NY	Volcano Hub (VHub)	Yes	A model that determines mass flow over natural terrain, e.g. volcanic flows and debris landslides, using a digital elevation model data. Designed to use with geographical information systems like ArcGIS and GRASS. Type: Model toolkit

Table AD.11. Wildfire Models

Program	Developed by	Available from	Public domain?	Description
ArcFuels	U.S. Forest Service (USFS)	USFS - Fire, Fuel Smoke Science Program	Yes	A toolbar for ArcMap that provides a logical flow from stand to landscape analysis of vegetation, fuel, and fire behavior for wildfire risk assessment. ArcFuels uses a number of different models in a simple user interface within ArcMap. ArcFuels incorporates data from models such as FlamMap and Forest Vegetation Simulator. Type: Tool

Program	Developed by	Available from	Public domain?	Description
BehavePlus	Systems for Environmental Management, U.S. Department of Agriculture (USDA) and USFS	USFS - Fire, Fuel, Smoke Science Program	Yes	A program that uses fuel and moisture conditions to model surface and fire spread rate and intensity, probability of ignition, fire size, spotting distance and tree mortality. Designed for fire management, wildfire prediction, prescribed fire planning, fuel hazard assessment, and education and training. Type: Model
FARSITE	Systems for Environmental Management	U.S. Forest Service - Fire, Fuel, Smoke Science Program	Yes	A model that uses topography, fuel, weather and wind data to simulate fire growth. Model accepts GIS raster data inputs, and outputs are compatible with GIS for visualization. Type: Model
Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS)	USFS	USFS - Fire, Fuel, Smoke Science Program	Yes	Links FVS, a forest vegetation model, with a model for fire behavior and fuel. This model provides managers with a tool that simulates fuel dynamics and potential fire behavior over time. Type: Fire model component of Forest Vegetation Simulator (FVS) forest growth Model
FireFamilyPlus (FFP)	USDA, USFS	USFS - Fire, Fuel, Smoke Science Program	Yes	Software that summarizes and analyzes daily weather observations and computing fire danger indexes based on the National Fire Danger Rating System. FFP can summarize weather climatology to produce climatological breakpoints for fire management decision making and can be used to set fire business thresholds. Type: Tool in suite of fire behavior/danger programs
FIREHARM (FIRE Hazard and Risk Model)	USDA and USFS, Rocky Mountain Research Station (RMRS) and Pacific Northwest Research Station	USFS - Fuel, Fire, Smoke Science Program	Yes	FIREHARM computes common measures of fire behavior, fire danger, and fire effects over space to use as variables to portray fire hazard spatially, and then computes fire risk by simulating daily fuel moistures over 18 years to compute fire measures over time. FIREHARM is more of a modeling platform than a fire model because it integrates previously developed fire simulation models into its structure and does not include any new fire behavior or effects simulation methods. Type: Model

Program	Developed by	Available from	Public domain?	Description
First Order Fire Effects Model	RMRS Fire, Fuel and Smoke Science Program; USFS Fire and Aviation Management	USFS - Fire, Fuel, Smoke Science Program	Yes	A computer program for predicting tree mortality, fuel consumption, smoke production, and soil heating caused by prescribed fire or wildfires. Type: Model
FlamMap	USFS	USFS - Fire, Fuel, Smoke Science Program	Yes	A program that computes potential fire behavior characteristics, e.g. spread rate, length, intensity, etc. There is no temporal component of FlamMap, it does not simulate variations in fire behavior caused by weather and diurnal fluctuations. It uses spatial data on topography and fuels to calculate fire behavior characteristics for a single set of environmental conditions. Raster outputs can be viewed in GIS. Type: Tool – part of a suite of fire behavior systems
Fuel and Fire Tools	USFS	USFS - Fire and Environmental Research Applications Team	Yes	Integrates the Fuel Characteristics Classification System (FCCS), Consume, FEPS, Pile Calculator, and Digital Photo Series into a single user interface. Type: Toolkit
FuelCalc	RMRS Station Fire, Fuel and Smoke Science Program; USFS Fire and Aviation Management	USFS - Fuel, Fire, Smoke Science Program	Yes	A fuel characteristics simulation software that calculates canopy fuel characteristics and simulates the effects of thinning, pruning, piling and broadcast burning on fuel characteristics. Type: Model
LandFire Data Access Tool	USDA and Department of the Interior (USDOI)	USDA and USDOI	Yes	An ArcGIS toolbar that allows users to interact and download data from the LandFire data distribution site. Type: Tool
LandFire Total Fuel Change Tool (LFTFC)	USDA and USDOI	USGS and USDOI	Yes	An ArcGIS toolbar that works in conjunction with the LandFire Data Access Tool and allows the user to create customized surface and canopy fuel layers for local applications. Type: Tool
NEXUS	USDA and USDOI	Pyrologix	Yes	Stand-level spreadsheet that links surface and crown fire prediction models. Linkage within ArcFuels10. Type: Tool that links separate models of surface and crown fire behavior

Appendix E: Climate Change Basics

This appendix provides a brief overview of certain key aspects of climate models used in the science of climate change, their use, and sources of processed climate model output with global coverage. Some of this material has been adapted from the succinct and useful Climate Trends and Projections – A Guide to Information and References developed by David Patte (2014) of the U.S. Fish and Wildlife Service, Pacific Region, to whom we are indebted.

The brief overview presented here is intended for non-specialists. Further details are available in the many reports of the Intergovernmental Panel on Climate Change (IPCC) at www.ipcc.ch, as well as numerous other publications.

Global vs. Regional vs. Local Scale

Disaster risk assessments are affected by the current and future local climate in a project area. General circulation models, also known as global climate models (GCMs, in both cases), are complex numerical simulation tools that are based on our best scientific understanding of the climate system that includes the atmosphere, hydrosphere, biosphere and lithosphere. These models operate on the foundation of well-established physics of the atmosphere, fluid dynamics, coupled atmosphere-ocean interactions, observational and theoretical knowledge of coupled terrestrial-atmosphere energy-water and biogeochemical cycles. Although global climate models are run on the world's top supercomputers, the sheer number of computations limits the spatial resolution and associated processes that the models can effectively resolve. However, GCMs are not specifically designed to simulate regional or local climate—their coarse spatial resolution (on the order of hundreds of kilometers) limits the direct application of output in regional and local analyses and decision-making (Daniels et al. 2012, Mearns et al. 2014). Downscaled climate projections (see below) currently supply the high-resolution climate outputs necessary for project risk assessment studies.

Climate Projections

GCMs are run by modeling agencies in countries all over the world (see Table D-2). Output from GCMs is provided through the coordinated Coupled Model Intercomparison Project (CMIP). Phase 3 of this project, termed CMIP3, was released in 2005 and 2006 for the Intergovernmental Panel on Climate Change's 4th Assessment (AR4). Phase 5 of this project, termed CMIP5, was released in 2012 for the 5th assessment (AR5).

The GCMs continued to develop between CMIP3 and CMIP5, so CMIP5 represents a more up-to-date representation of the state-of-science. Another significant way in which the CMIP3 and CMIP5 experiments differ is in the prescriptions for future scenarios, termed forcings. CMIP3 uses future scenarios from the Special Report on Emission Scenarios (SRES; Nackicenovic et al., 2011). Each SRES (e.g., A2B) represents a theorized pathway of future greenhouse gas emissions, which depends on changes in economics, population growth, technology, and policy choices made throughout the world. The IPCC summarizes these scenarios as follows (http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=3):

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The SRES approach of CMIP3 attempts to provide forecasts of the future nature of the world and society. The dependence on socioeconomic scenarios introduces a large amount of uncertainty. In contrast, CMIP5 abandoned the attempt to predict future socioeconomic conditions and instead provides a range of different future greenhouse gas concentration assumptions, known as Representative Concentration Pathways (RCPs). For example, RCP6 is a possible emission/climate change scenario in which atmospheric greenhouse gas concentrations are stabilized so as not to exceed a radiative forcing equivalent of 6 W/m^2 in 2100, equivalent to about 850 ppmv CO_2 (for perspective, the current atmospheric CO_2 level is about 400 ppmv). CMIP5 examined RCPs from 2.6 to 8.5 W/m^2. RCP8.5 is the most extreme emissions scenario in which greenhouse gas concentrations continue to rise unchecked through the end of the century leading to a radiative forcing of 8.5 W/m^2 (equivalent to about 1,370 ppmv CO^2) by 2100.

SRES and RCP scenarios do not have a one-to-one match. In general, RCP4.5 is similar to the B1 SRES; RCP6 is slightly lower than the A1B SRES, and RCP8.5 is similar to the A1F1 SRES in terms of greenhouse gas concentrations (see Jubb et al., ND).

Downscaled Climate Projections

Downscaling is the process of translating the climate information from the GCMs from their native coarse resolution to a much finer resolution. There are two primary approaches to downscaling: statistical and dynamical. Dynamical downscaling is achieved by running regional climate models with forcing from the GCMs. This is a demanding task, for which reason dynamical downscaling outputs have limited availability. Mearns et al. (2014) provide a review of the methods and their strengths and weaknesses. Currently, the most readily available form of finer-resolution climate projections is from statistical downscaling. Statistical downscaling uses the statistical relationships between fine resolution grid points in an observational dataset to remove biases (e.g., shifts in the mean or distribution) from the GCM output, capture local meteorological relationships and to spatially 'interpolate' these to a finer resolution. Bias-corrected and spatially disaggregated downscaling aims to preserve the

Program	Developed by	Available from	Public domain?	Description
• WIFIRE Firemap	University of California, San Diego	UC San Diego - Supercomputer Center	Yes	A web platform that performs predictive modeling and analysis of fires and real-time forecasting. Also provides access to information on past fires, past and current weather conditions, weather forecasts, satellite detections, and information on vegetation and landscapes. Type: Web-modeling tool
• Wildland-Urban Interface Fire Dynamics Simulator (WFDS)	National Institute of Standards and Technology (NIST) and USFS	USFS - Fire and Environmental Research Applications Team	Yes	An extension to NIST's Fire Dynamics Simulator (FDS) which uses computational fluid dynamics to simulate fire behavior. Type: Extension to FDS
• WindNinja	USDA and USFS	USFS - Fire Lab	Yes	A program that spatially computes varying wind fields for wildland fire application. Outputs to be used in programs such as FARSITE and FlamMap or to be displayed in GIS. Type: Model

References, Appendix D

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projected climate change (both changes in the mean and extremes) from the GCM outputs for a future period (e.g., 2040-2065) with respect to a baseline period (commonly 1950-2005).

Empirical statistical downscaling methods use cross-scale relationships that have been derived from observed data, and apply these to climate model data. Statistical downscaling methods have the advantage of being computationally inexpensive, able to access finer scales than dynamical methods and applicable to parameters that cannot be directly obtained from dynamical downscaling outputs. They require observational data at the desired scale for a long enough period to allow the method to be well trained and validated. This means that downscaled data may not have effective bias correction in areas where weather measurements are sparse. The main drawbacks of statistical downscaling methods are that they assume that the derived cross-scale relationships remain stable when the climate is perturbed, they cannot effectively accommodate regional feedbacks and, in some methods, can lack coherency among multiple climate variables." (IPCC 2007).

There are not many different websites that serve downscaled climate data. Various countries have supported local downscaling efforts. Some major global sources of downscaled climate data are listed in Table D-1.

Frequently Asked Questions

How are GCMs different from one another?

Although there are many similarities between the models (reflecting the current state of the science), the differences arise in the finer details (e.g., how they simulate cloud generation or feedback processes, differences in coupled atmosphere-ocean processes) and thus result in differences in projected outputs. Although this may seem disconcerting, these differences can be embraced using an ensemble approach (where projected outputs are treated as equally like outcome) similar to that done with weather predictions.

Should I use a single model or multi-model ensemble average?

For many decision support or analytic needs, the multi-model ensemble approach is recommended (as suggested in Daniels et al. 2012, Mote et al. 2011, and Snover et al. 2013). In this approach, the multi-model ensemble mean provides information about the most likely future outcome, and differences over the ensemble of models provide information about the uncertainty.

Alternatively, since extremes can be important to decision making or analysis (e.g., worst case scenarios are important in the design, planning, and risk analysis for high-value infrastructure), one can use a scenario study by choosing to study several models that are extreme to the full spectrum of model variation. Given the uncertainty in GCMs, it may be advisable to not use the most extreme model but rather to pick one that is near the upper end (e.g., 90^{th} percentile) of the range of the variable of interest.

How do I determine the most accurate climate projection? How accurate are the projections?

Much of the analysis and published scientific literature on the use of climate models suggests that it is futile to attempt to identify the "most accurate" climate scenario due to uncertainties in future greenhouse gas emissions, modeling uncertainties, and other factors. Major contributors to uncertainty are imperfect knowledge of (1) the drivers of change, chiefly the sources and sinks of anthropogenic greenhouse gases and aerosols; (2) the response of the climate system to those drivers; and (3) how unforced variability may mask the forced response to drivers. The ability of individual models to simulate historic climate may not accurately reflect their ability to simulate future climate, reiterating the importance of using multiple models for planning purposes.

Downscaling projects are intended to increase precision (not accuracy) by providing information at regional scales. They do not reduce the uncertainties discussed above.

In addition to uncertainty considerations, Snover et al. (2013) point out that "the most appropriate scenarios for a particular analysis will not necessarily be the most appropriate for another due to differences in local climate drivers, biophysical linkages to climate, decision characteristics, and how well a model simulates the climate parameters and processes of interest."

Snover et al. advise as follows: "Given these complexities, we recommend interaction among climate scientists, natural and physical scientists, and decision makers throughout the process of choosing and using climate change scenarios for ecological impact assessment."

Table D-1. Selected Downscaled Climate Data and Impact Model Sources

Source	Description
NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP).	The NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset is comprised of downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 5 (CMIP5) and across two of the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs)
Downscaled Global Climate Data by E. P. Maurer (Santa Clara University).	Maurer downscaled 150 years of global climate data from 1950 to 2099 from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) using a bias correction/spatial downscaling method.
Consultative Group for International Agricultural Research (CGIAR).	The CCAFS-Climate data portal provides global and regional future high-resolution climate datasets that serve as a basis for assessing the climate change impacts and adaptation in a variety of fields including biodiversity, agricultural and livestock production, and ecosystem services and hydrology. The data distributed here are in ARC GRID, and ARC ASCII format, in decimal degrees and datum WGS84.
Climate Change Knowledge Portal (CCKP).	The World Bank's CCKP is a central hub of information, data and reports about climate change around the world. Data include historical climate data, projected climate data, and climate data by sectors.
Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)	ISIMIP focuses on climate impact models. It provides output from simulation model experiments that convert GCM output to predictions of flow, water quality, ecological responses, disease risks, and so on.

Table D-2: Global Climate/General Circulation Models (GCMs)

Program	Developed By	Available From	Description
ACCESS1.3	Commonwealth Scientific and Industrial Research Organization (CSIRO) and the Bureau of Meteorology (BOM)	Earth System Grid Federation/Department of Energy	The Australian Community Climate and Earth System Simulator (ACCESS) is a coupled Earth System Model (ESM), which was extended to include land and ocean carbon cycle components to assess climate impact and conduct adaptation analyses.

Program	Developed By	Available From	Description
BCC_CSM1.1(m)	Beijing Climate Center (BCC)	Beijing Climate Center (BCC)	A fully coupled global climate-carbon model with an atmospheric resolution of 1m. The model couples BCC_AGCM2.1, the atmospheric component, MOM4-L40, the ocean component, BCC_AVIM1.0, the land component, and SIS, the ice component.
CCSM4	National Center for Atmospheric Research (NCAR)	National Center for Atmospheric Research (NCAR)	The Community Climate System Model (CCSM) is a climate model that simulates the Earth's past, present and future climate systems by coupling four separate models (atmospheric, oceanic, land surface, and sea ice)
CESM1.2z	National Science Foundation (NSF), Department of Energy (DOE), National Center for Atmospheric Research (NCAR)	National Science Foundation (NSF) and National Center for Atmospheric Research (NCAR)	The Community Earth System Model (CESM) is a fully-coupled global climate model that simulates the Earth's climate state at different times. CESM incorporates 6 model components: atmosphere, land, sea ice, ocean, land ice, and river. Input data are available from a public subversion input data repository.
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Queensland Climate Change Centre of Excellence (QCCCE)	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	The CSIRO Mark 3.6 (Mk3.6) global climate model (GCM) was developed from the earlier Mk3.5 version. It is a coupled atmosphere-ocean model with dynamic sea-ice. It also has a soil-canopy scheme with prescribed vegetation properties. The ocean, sea-ice and soil-canopy models are unchanged between Mk3.5 and Mk3.6. The main differences between Mk3.5 and Mk3.6 are the inclusion of an interactive aerosol treatment and an updated radiation scheme in Mk3.6.
GEOS-5	NASA Global Modeling and Assimilation Office (GMAO)	National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO)	The Atmosphere-Ocean General Circulation Model (AOGCM) of the Goddard Earth Observing System Model version 5 (GEOS-5) system is a fully coupled model with predictive capabilities for atmosphere, land, ocean and ice states.
GFDL-CM3	Geophysical Fluid Dynamics Laboratory (GFDL)	National Oceanographic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory	A coupled global climate model that includes finer modeled processes than its predecessor, such as deep and shallow cumulus convection, cloud droplet activation by aerosols, atmospheric chemistry driven by emissions with advective, convective, and turbulent transport, and a new dynamic vegetation component.
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory (GFDL)	National Oceanographic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory	GFDL's first Earth System Models (ESMs) to advance our understanding of how the Earth's biogeochemical cycles, including human actions, interact with the climate system. Like GFDL's physical climate models, these simulation tools are based on an atmospheric circulation model coupled with an oceanic circulation model, with representations of land, sea ice and iceberg dynamics. ESMs incorporate interactive biogeochemistry, including the carbon cycle.
GISS-E2-H	NASA Goddard Institute for Space Studies (GISS)	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS)	The Goddard Institute for Space Studies (GISS) global climate model (GCM) ModelE is a coupled atmosphere-ocean model that simulates different configurations of Earth System Models (ESMs), including interactive atmospheric chemistry, aerosols, carbon cycle and standard atmosphere, ocean, sea ice, and land surface components.

Program	Developed By	Available From	Description
HadGem2-ES	Met Office Hadley Centre (MOHC) -- additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais (INPE)	European Network for Earth System Modelling	The Hadley Centre Global Environment Model version 2 (HadGem2-ES) is a coupled ESM and includes an Earth system component as a standard component and a vertical extension in the atmosphere for a well-resolved stratosphere. The Earth systems included in the component are dynamic vegetation, ocean biology, and atmospheric chemistry.
IPSL-CM5A-LR	Institut Pierre Simon Laplace	European Network for Earth System Modeling (ENES)	A model that includes 5 component models representing the Earth System climate and its carbon cycle: LMDz (atmosphere), NEMO (ocean, oceanic biogeochemistry and sea-ice), ORCHIDEE (continental surfaces and vegetation), and INCA (atmospheric chemistry), coupled through OASIS. IPSLESM, available in different configurations at different resolutions, is in permanent evolution to reflect state-of-the-art numerical climate science. IPSL-CM5 is used in about 50 European projects, and more than 550 projects access its IPCC result database.
MIROC5	The University of Tokyo, Atmosphere and Ocean Research Institute (AORI), National Institute for Environmental Studies, Tsukuba, Japan (NIES), and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)	A new version of the atmosphere-ocean general circulation model cooperatively produced by the Japanese research community, known as the Model for Interdisciplinary research on Climate (MIROC), has recently been developed. A century-long control experiment was performed using the new version (MIROC5) with the standard resolution of the T85 atmosphere and 1-degree ocean models.
MIROC-ESM	The University of Tokyo, Atmosphere and Ocean Research Institute (AORI), National Institute for Environmental Studies, Tsukuba, Japan (NIES), and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP)	An Earth System Model named "MIROC-ESM" (Model for Interdisciplinary Research on Climate - Earth System Model). A comprehensive atmospheric general circulation model (MIROC-AGCM) including an on-line aerosol component (SPRINTARS), an ocean GCM with sea-ice component (COCO), and a land surface model (MATSIRO) are interactively coupled in MIROC. These atmosphere, ocean, and land surface components, as well as a river routine, are coupled by a flux. On the basis of MIROC, MIROC-ESM further includes an atmospheric chemistry component (CHASER), a nutrient-phytoplankton-zooplankton-detritus (NPZD) type ocean ecosystem component, and a terrestrial ecosystem component dealing with dynamic vegetation (SEIB-DGVM).
MPI-ESM-LR	Max Planck Institute for Meteorology (MPIM)	Max Planck Institute for Meteorology (MPI-M)	The MPI-ESM-LR model is comprised of general circulation models for the atmosphere and ocean, and subsystem models for land and vegetation and marine biochemistry. This version of the model includes a dynamic vegetation component and land use transition approach for anthropogenic land-cover change.

Program	Developed By	Available From	Description
MRI-CGCM3	Meteorological Research Institute (MRI), Tsukuba, Japan	Intergovernmental Panel on Climate Change (IPCC) Data Distribution Center)	This model is an overall upgrade of MRI's former climate model MRI-CGCM2 series. MRI-CGCM3 is composed of atmosphere-land, aerosol, and ocean-ice models, and is a subset of the MRI's Earth system model MRI-ESM1. Atmospheric component MRI-AGCM3 is interactively coupled with aerosol model to represent direct and indirect effects of aerosols with a new cloud microphysics scheme.
NCEP-CFSv2	Center for Ocean-Land-Atmosphere (COLA) Studies and National Centers for Environmental Prediction (NCEP)	National Center for Environmental Prediction (NCEP) - Climate Forecast System	A fully coupled model that represents the interactions between the Earth's atmosphere, oceans, land, and sea ice. The most recent version ensures a continuity of the climate record and provides a valuable up-to-date dataset and improved seasonal and subseasonal forecasts.
NorESM1-M	A multi-institutional, coordinated climate research project in Norway, funded by the Research Council of Norway for the period 2011-2014.	European Network for Earth System Modeling (ENES)	The core version of the Norwegian Climate Center's Earth System Model, is named NorESM1-M. The NorESM family of models are based on the Community Climate System Model version 4 (CCSM4) of the University Corporation for Atmospheric Research, but differs from the latter by an isopycnic coordinate ocean model and advanced chemistry-aerosol-cloud-radiation interaction schemes. NorESM1-M has a horizontal resolution of approximately 2° for the atmosphere and land components and 1° for the ocean and ice components.

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Appendix I: Terms of Reference

Use the following templates to develop terms of reference for disaster and climate change risk assessment. Two templates are provided, the first for simpler assessments and the second for more detailed and complex assessments.

TERMS OF REFERENCE

Disaster and Climate Change Risk Assessment – Project Level (Simple)

1. Background and Justification
   1.1. Provide a brief justification for the existence of this project/contract explaining why the project/contract is needed. This will help the consulting firms to better understand the overall direction and context of the project/contract and its goals. This justification should be clear and precise to identify quantifiable measure of success for the end of the project. It could include the following information, which can be organized and tailored based on your preference:
   - Project context
     - Provide project-specific information and background. This should include site location and setting, project description, and schedule and costs.
   - Characteristics and criticality
     - Provide information on the project's characteristics, including identification of specific project components.
     - Briefly introduce the hazards of concern and identify illustrative failure modes for context and justification.
   - Existing or planned project designs or plans
     - If designs are available, describe whether hazard mitigation and climate change adaptation measures were integrated into the project design and, if so, how they were identified/assessed.
     - If designs are planned or underway, describe the percentage complete and/or anticipated timeframe for completion.
   - Overview of regional considerations, including climate change
     - Describe the identified/perceived vulnerabilities to climate change, such as situational understanding of the climate change related risks (direct and indirect) to the project(s), geographic location, the sector or institutional area.
     - Identify any recent or projected activities that are critical to consider, including population trends (including urban growth and planning), broader economic and market trends, institutional or governance trends, or other donor activities.
     - Describe the institutional arrangements of the project beneficiary and any other relevant management or organizational frameworks that may be useful for the consultant to better understand the adaptive capacity of the project, and any known capacity issues or challenges.
   - Other relevant information and activities
     - Describe any existing studies, models, or data that have been produced.
2. Objectives
   2.1. The overall purpose of this consultancy is to develop a disaster and climate risk assessment (DRA) and an accompanying disaster and climate risk management plan (DRMP) for the [project name] project to provide resiliency and improve or enhance the project's sustainability.
3. Scope of Services
   3.1. The DRA is expected to focus on the specific project-related issues that have been identified as

relevant for this risk assessment, and use accepted or standard methods to conduct a [qualitative and/or quantitative] analysis. The disaster and climate risks will be evaluated for [seismic, volcanic, landslide, tsunami, hurricane wind, storm surge, inland flooding, coastal flooding, sea level rise, drought and/or heatwave] hazards in the study area of [location] and specifically for the: [components/aspects] of the operation.

3.2. This analysis will provide a [qualitative and/or quantitative] measure of the baseline risk conditions, as well as those of any proposed design or operation alternatives (that is, on a first instance for the existing conditions without the operation, and on a second instance for the newly generated conditions after the operation is in place), for (i) the operation itself and (ii) the operation's surrounding area and communities.

In assessing the risk for the surrounding communities, special care should be taken to identify (i) the marginal risk and (ii) additional impacts to communities as a result of implementation of the operation. This shall be done keeping in mind the difference between risk and impacts, where risk refers to the end result of combining the magnitude of a consequence with its frequency of occurrence, whereas impacts refer to individual and frequency-independent consequences. Hence, there may be cases where implementation generates new or additional impacts on its surroundings that would not occur without the project, but reduces the overall risk. Therefore, the marginal risk refers to identifying how the risk (including both recurrent-small and rare-large events) changes for the surroundings, with respect to the situation without the operation, making sure that the operation does not exacerbate the risk for its surroundings. In addition to this, the newly generated impacts shall also be identified and assessed.

3.3. Based on a careful analysis of these results, the consultancy should provide recommendations and design/management guidelines aimed at reducing or managing the disaster risk of both the operation and the surrounding area, as well as a management plan for the identified impacts on surrounding communities and population.

4. Key Activities

4.1. Conduct a qualitative risk assessment.

4.1.1. Gather data.

Gather all valuable data regarding studies, documents and considerations that the project may already have, and document how and to what extent disaster and climate risk management measures have already been incorporated, as well as identify gaps.

4.1.2. Perform a complete qualitative risk assessment.

This can be done through a workshop where disaster and climate risk experts work with technical personnel from the design/construction firms and the operation's executing agency to discuss and gauge all possible risks, contributing factors, potential consequences and intervention measures. Other qualitative techniques include formally applying the Delphi method of consulting expert opinion or using risk matrices. Indicate whether it is possible to characterize and estimate the order of magnitude of possible social, economic, and environmental impacts that would not be possible without the existence of the project.

4.1.3. Build a disaster and climate risk management plan.

Using the results from the previous activities, build a risk management plan for those features of the operation that are deemed to not condition the technical and/or economic viability of the project. On the other hand, if specific features of the operation are found to condition the project's viability, these must be assessed quantitatively.]

4.2. Conduct a quantitative risk assessment.

4.2.1. Conduct a baseline (current conditions, pre-interventions) [input hazard(s)] risk assessment for (a) the operation, and (b) the communities of [names of communities] located in the influence area.

[Only for hydrometeorological hazards: For each of these analyses, consider two configurations of the risk model, without considering climate change, and with climate change]. This activity comprises the following specific activities:

4.2.1.1. Hazard evaluation: Evaluate the [input hazard(s)] hazard in terms of spatial extent, intensity and frequency of occurrence. For this, select one or more individual hazard scenarios, which may be reproductions of historical events or modeled design or worst-case scenarios. [Input specific simplified method according to specific hazard]. [Only for hydrometeorological hazards: Two hazard conditions should be considered, without considering climate change, and with climate change].

4.2.1.2. Exposure evaluation: Assemble a geodatabase of all the physical assets (infrastructure and buildings) and social assets (population) that are part of (i) the operation itself, if something already exists and comprises multiple assets that are spatially distributed, and (ii) the surrounding area of influence (nearby communities or settlements). These must be characterized by their physical conditions, their use sectors, and their economic value.

4.2.1.3. Vulnerability evaluation: Evaluate the vulnerability conditions of (i) the project itself (if something already exists) and (ii) nearby assets and population. Best professional judgement and expert opinion should be used to assign this characteristic to individual assets (for the case of the operation) and grouped assets (for multiple assets in surrounding communities).

4.2.1.4. Risk evaluation: Evaluate the resulting risk from the combination of hazard, exposure and vulnerability, evaluated above. For this, use GIS tools to obtain the values of the hazard intensity ([input intensity measures corresponding to each hazard(s)]) for the location of each exposed asset, determine the corresponding negative effect/damage level expected for each asset under the specific hazard intensity, and finally associate an economic value to the computed damage levels to obtain risk. [Only for hydrometeorological hazards: this calculation shall be carried out twice, using the hazard conditions without considering climate change, and with climate change].

4.2.2. Conduct a [input hazard(s)] Risk Assessment including the operation and alternatives.

Based on the results obtained from activity 4.2.1, introduce the proposed project, together with risk reduction/mitigation/intervention measures or design alternatives, and conduct a second [input hazard(s)] risk assessment, using the same methods and conditions as in activity 4.2.1, now introducing these interventions. For this, modifications must be made to the hazard, exposure, or vulnerability evaluations if appropriate, responding to the changes that introducing the operation and intervention measures may cause.

The results of each evaluation should be expressed as estimated economic losses. These should be compared among themselves, but more importantly, to the results from activity 4.2.1, analyzing the differences in losses between the baseline and the post-operation implementation conditions. Hazard and risk maps should also be developed for the scenarios studied, and they should be compared to the maps from activity 4.2.1.

4.2.3. Build a disaster and climate risk management plan.

Using the results from the previous activities, build a risk management plan that considers additional measures to further reduce the risk and to control the expected impacts.

5. Expected Outcome and Deliverables
   5.1. Report 1: Workplan and detailed study methodology
   5.2. [Report 2: Risk and data diagnosis from the qualitative risk assessment (activity 4.1.1.)
   5.3. Report 3: Results from the qualitative risk assessment (activity 4.1.2.)
   5.4. Report 4: Disaster and climate risk management plan from the qualitative risk assessment (activity 4.1.3.)]

5.5. Report 5: Results from the baseline quantitative risk assessment (activity 4.2.1.)
5.6. Report 6: Results from the quantitative risk assessment including the operations and intervention measures (activity 4.2.2.)
5.7. Report 7: Disaster and climate risk management plan from the quantitative risk assessment (activity 4.2.3.)

6. Project Schedule and Milestones
   6.1. Report 1 must be presented within 10 calendar days after the execution of the contract.
   6.2. Report 2 must be presented within 25 calendar days after the execution of the contract.
   6.3. Report 3 must be presented within 40 calendar days after the execution of the contract.
   6.4. Report 4 must be presented within 50 calendar days after the execution of the contract.
   6.5. Report 5 must be presented within 80 calendar days after the execution of the contract.
   6.6. Report 6 must be presented within 120 calendar days after the execution of the contract.
   6.7. Report 7 must be presented within 130 calendar days after the execution of the contract.
7. Reporting Requirements
   7.1. Submit all reports in the following formats: (i) the relevant electronic files in MS Word, Excel, or other acceptable application (must include all annexes and appendices) and (ii) an electronic PDF file. These reports and electronic files should be delivered within the timeframes mentioned above.
   7.2. Provide verified working copies of all digital map files (.shp, .tiff, .grd, .gdb, .mxd, etc.), models, databases, and other files created during the consultancy.
   7.3. Additionally, major findings of the consultancy must be summarized in an MS PowerPoint presentation.
8. Acceptance Criteria
   8.1. Describe the specific requirements for acceptance: establish responsibilities for the technical requirements and approval of products.
9. Other Requirements
   9.1. Describe any special requirements, such as security requirements, any IT access restrictions/requirements, or system downtime/maintenance if required.
   9.2. Clarify the specific risk method to be followed.
   9.3. Identify the required qualifications of key experts and staff. At a minimum, the team leader should have demonstrated experience with disaster and climate change risk assessment and/or risk management, as well as experience in the sector and geographic region of interest. Multi-disciplinary teams that span the project and risk requirements should be encouraged. Additional team-member requirements could include post-graduate degrees in a field of science relevant to the project and/or to climate change. Experience in the region and country of interest is also recommended, as is relevant language proficiency.
10. Supervision and Reporting
    10.1. Describe the specific requirements: establish responsibilities for the technical requirements and approval of products.
11. Schedule of Payments
    11.1. Describe the schedule of payments according to products.

TERMS OF REFERENCE
Climate and Disaster Risk Assessment – Project Level (Full)

1. Background and Justification
   1.1. (Provide a brief justification for the existence of this project/contract explaining why the project/contract is needed. This will help the consulting firms to better understand the overall direction and context of the project/contract and its goals. This justification should be clear and precise to identify quantifiable measure of success for the end of the project. This could include the following information, which can be organized and tailored based on your preference:
   - Describe the Project Context.
     - Provide project specific information and background. This should include site location and setting, project description, and schedule and costs.
   - Describe the Characteristics and Criticality of the Project.
     - Provide information on your project's characteristics, including identification of specific project components.
     - Introduce the hazards of concern. You do not need to go into much detail at this point, simply introduce the hazards that are the focus of the study and identify illustrative failure modes for context and justification.
   - Identify Relevant Project Specific Designs or Plans. If there are any relevant design activities (existing, planned, or underway), identify them.
     - If designs are available, describe whether hazard mitigation and climate change adaptation measures were integrated into the project design and, if so, how those measures were identified/assessed.
     - If designs are planned or underway, describe the percentage complete and/or anticipated time-frame that they would be available. In the Scope of Work section (below), you will need to specify how the consultant should interact with the design team/consultant to integrate findings.
   - Provide an Overview of Regional Considerations, including Climate Change. Describe any regional considerations that may be useful for the consultant to better understand the project's exposure and/or vulnerability. This could include:
     - A brief description of the identified/perceived vulnerabilities to climate change. This could include situational understanding of the climate change related risks (direct and indirect) to the project(s), geographic location, the sector or institutional area.
     - Identify any recent or projected activities that are critical to consider. This could include consideration of population trends (including urban growth and planning), broader economic and market trends, institutional or governance trends or other donor activities.
     - Describe the institutional arrangements of the beneficiary to the project and any other relevant management or organizational frameworks that may be useful for the consultant to better understand the adaptive capacity of the project. If there are known capacity issues or challenges, describe them here.
   - Identify other Relevant Information and Activities. Provide an overview of existing or planned studies that may be useful to the consultant. Consider:
     - Other existing studies and activities that may provide useful information. If there are existing studies, models, or data that have been produced, describe them here.)
2. Objectives

   2.1. The overall purpose of this consultancy is to develop a Disaster and Climate Risk Assessment (DRA) and an accompanying Disaster and Climate Risk Management Plan (DRMP) for the [project name] project to provide resiliency and improve or enhance the project's sustainability.

3. Scope of Services

3.1. The DRA is expected to go beyond a generic literature review of all possible risks, it is expected to focus on the specific project-related issues that have been identified as relevant for this risk assessment, and which are specified next, and use accepted or standard methods to conduct a [qualitative and/or quantitative] analysis. The disaster and climate risks shall be evaluated for [seismic, volcanic, landslide, tsunami, hurricane wind, storm surge, inland flooding, coastal flooding, sea level rise, drought and/or heatwave] hazards in the study area of [location] and specifically for the following components or aspects of the operation: [components/aspects].

3.2. This analysis shall provide a [qualitative and/or quantitative] measure of the baseline risk conditions, as well as those of any proposed design or operation alternatives (that is, on a first instance for the existing conditions without the operation, and on a second instance for the newly generated conditions after the operation is in place), for (i) the operation itself and (ii) for the operation's surrounding area and communities. To conduct these assessments, the consultancy will [qualitatively and/or quantitatively] evaluate the hazard conditions in terms of its spatial extent, intensity and frequency of occurrence (for the above mentioned hazards), the project's and surrounding communities' physical vulnerability to these hazards in terms of their expected behavior/response to being affected, and the expected levels of damage, losses and negative effects to be sustained by the population, ecosystems and infrastructure of the operation and surrounding communities. It is important to highlight that in assessing the risk for the surrounding communities, special care should be taken to identify (i) the marginal risk and (ii) additional impacts for these as a result of the implementation of the operation. This shall be done keeping in mind the difference between risk and impacts, where risk refers to the end result of combining the magnitude of a consequence with its frequency of occurrence, whereas impacts refer to the individual and frequency-independent consequences. Hence, there may be cases where the implementation of an operation generates new or additional impacts on its surroundings that would not be possible without the project, but overall reduces the risk. Therefore, the marginal risk refers to identifying how the risk (including both recurrent-small and rare-large events) changes for the surroundings, with respect to the situation without the operation, making sure that the operation does not exacerbate the risk for its surroundings. In addition to this, the newly generated impacts shall also be identified and assessed.

3.3. Based on a careful analysis of these results, the consultancy should provide recommendations and design/management guidelines aimed at reducing or managing the disaster risk of both the operation and the surrounding area, as well as a management plan for the identified impacts on surrounding communities and population.

4. Key Activities

4.1. [Conduct a qualitative risk assessment.

4.1.1. Gather data.

Gather all valuable data regarding studies, documents and considerations that the project may already have, so as to document how and to what extent disaster and climate risk management measures have already been incorporated in the project designs and in general in the area of study, as well as to identify the gaps that exist.

4.1.2. Perform a complete qualitative risk assessment.

This can be done through a workshop where disaster and climate risk experts work with technical personnel from the design/construction firms and the operation's executing agency to discuss and gauge all possible risks, contributing factors, potential consequences and intervention measures. Other qualitative techniques include formally applying the Delphi method of consulting expert opinion or using risk matrices. It must be indicated if it is possible to characterize and estimate the order of magnitude of possible social, economic and environmental impacts that would not be possible without the existence of the project.

4.1.3. Build a Disaster and Climate risk Management Plan.

Using the results from the previous activities, build a risk management plan for those features of the operation that are deemed to not condition the technical and/or economic viability of the project. On the other hand, if specific features of the operation are found to condition the project's viability, these must be assessed quantitatively.]

4.2. Conduct a quantitative risk assessment.

4.2.1. Conduct a baseline (current conditions, pre-interventions) Probabilistic [input hazard(s)] Risk Assessment for (a) the operation, and (b) the communities of [names of communities] located in the influence area.

[Only for hydrometeorological hazards: For each of these analyses, two configurations of the risk model should be considered, without considering climate change, and with climate change].

This activity comprises the following specific activities:

4.2.1.1. Hazard evaluation: probabilistically evaluate the [input hazard(s)] hazard in terms of spatial extent, intensity and probability of occurrence. [Only for hydrometeorological hazards: Two hazard conditions should be considered, without considering climate change, and with climate change].

4.2.1.2. Exposure evaluation: assemble an updated geodatabase of all the physical assets (infrastructure and buildings) and social assets (population) that are part of (i) the operation itself, if something already exists and comprises multiple assets that are spatially distributed, and (ii) the surrounding area of influence (nearby communities or settlements).

4.2.1.3. Vulnerability evaluation: probabilistically evaluate the vulnerability conditions of (i) the project itself (if something already exists) and (ii) nearby assets and population.

4.2.1.4. Risk evaluation: probabilistically evaluate the resulting risk from the combination of hazard, exposure and vulnerability, evaluated above. [Only for hydrometeorological hazards: this calculation shall be carried out twice, using the hazard model without considering climate change, and with climate change].

4.2.2. Conduct a Probabilistic [input hazard(s)] Risk Assessment including the operation and proposed alternatives.

Based on the results obtained from activity 4.2.1, introduce the proposed project, together with risk reduction/mitigation/intervention measures or design alternatives, and conduct a second Probabilistic [input hazard(s)] Risk Assessment, using the same methods and conditions as in activity 4.2.1, now introducing these interventions. This activity comprises the following specific activities:

4.2.2.1. Propose risk reduction measures: based on the risk evaluations from activity 4.2, provide structural (physical construction or engineering techniques or technology) and/or non-structural (policies, laws, training or education) design guidelines and strategies to reduce and manage the [input hazard(s)] risk of the area and increase its adaptive capacity.

4.2.2.2. Run a second Probabilistic [input hazard(s)] Risk Assessment: for this, modifications must be made to the hazard, exposure or vulnerability evaluations if appropriate, responding to the changes that introducing the operation and intervention measures may cause.

The results of this new evaluation shall be expressed through the estimated economic losses, and these should be compared among themselves, but more importantly, to the results from activity 4.2.1, analyzing the differences in losses between the baseline and the post-operation implementation conditions. Hazard and risk maps should also be developed and compared to the maps from activity 4.2.1.

4.2.3. Build a Disaster and Climate risk Management Plan.

Using the results from the previous activities, build a risk management plan that considers additional measures to further reduce the risk and to control the expected impacts.

5. Expected Outcome and Deliverables
5.
    5.1. Report 1: workplan and detailed study methodology
    5.2. [Report 2: risk and data diagnosis and results from the qualitative risk assessment (activity 4.1.1. and 4.1.2.)
    5.3. Report 3: disaster & climate risk management plan from the qualitative risk assessment (activity 4.1.3.)]
    5.4. Report 4: results from the baseline quantitative hazard assessment (activity 4.2.1.1.)
    5.5. Report 5: results from the baseline quantitative exposure, vulnerability and risk assessment (activities 4.2.1.2 – 4.2.1.4.)
    5.6. Report 6: operation design and risk reduction and intervention measures (activity 4.2.2.1.)
    5.7. Report 7: results from the quantitative risk assessment including the operation and intervention measures (activity 4.2.2.2.)
    5.8. Report 8: disaster & climate risk management plan from the quantitative risk assessment (activity 4.2.3.)
6. Project Schedule and Milestones
6.
    6.1. Report 1 must be presented within 10 calendar days after the execution of the contract.
    6.2. Report 2 must be presented within 40 calendar days after the execution of the contract.
    6.3. Report 3 must be presented within 50 calendar days after the execution of the contract.
    6.4. Report 4 must be presented within 110 calendar days after the execution of the contract.
    6.5. Report 5 must be presented within 150 calendar days after the execution of the contract.
    6.6. Report 6 must be presented within 170 calendar days after the execution of the contract.
    6.7. Report 7 must be presented within 220 calendar days after the execution of the contract.
    6.8. Report 8 must be presented within 240 calendar days after the execution of the contract.
7. Reporting Requirements
7.
    7.1. All reports will be delivered as follows: i) the relevant electronic files in MS Word, Excel, or other application (must include all annexes and appendices); ii) an electronic PDF file for each full report. These reports and electronic files should be delivered within the time limits mentioned above.
    7.2. Provide verified working copies of all digital map files (.shp, .tiff, .grd, .gdb, .mxd, etc.), models, databases, and other files created during the consultancy.
    7.3. Additionally, major findings of the consultancy must be summarized in a MS PowerPoint presentation.
8. Acceptance Criteria
8.
    8.1. (Describe the specific requirements for acceptance: establish responsibilities for the technical requirements and approval of products.)
9. Other Requirements
9.
    9.1. The consulting firm should follow the methodology detailed next to conduct activity 4.2.
    Probabilistic [hazard(s)] Risk Assessment methodology: a probabilistic risk assessment seeks to estimate the losses (economic or human) that in average can be expected to occur with a certain temporal recurrence in a determined set of assets or population that is exposed to one or more natural hazards. A study of this nature consists of four modules – hazard module, exposure module, vulnerability module and risk module – each of which is explained next.
    Hazard module: the hazard module of a probabilistic risk assessment consists of a set of stochastic

events which as a whole represent the entire universe of possibilities of [hazard(s)] in the study area. Each of these events must contain the spatial distribution of the intensity measure selected for analysis – [hazard intensities] in this case –, and an associated frequency of occurrence, so that a probability distribution can be built for the selected intensity measure.
[Input specific probabilistic modeling method according to specific hazard]. [Only for hydrometeorological hazards: Climate change must be included, using future climatic projections drawn from similar conditions as the Intergovernmental Panel on Climate Change (IPCC) scenarios. Regional climate model projections should be used (if possible), applying downscaling techniques when necessary. The resulting projections should directly be used to alter or modify the historic analysis and subsequent process of generating stochastic events. To do this, it is recommended to use weather generator models such as the non-parametric K-Nearest Neighbor[1] (Simonovic and Peck, 2009), SDSM[2] (Wilby and Dawson, s.f.) or similar.]
Exposure module: the exposure module of a probabilistic risk assessment consists of a geo-referenced database containing all of the physical assets, as well as population, that may be affected by a natural hazard. The hazard module (explained above) will affect what is contained in this module. This module must properly characterize the assets, storing attributes such as their physical conditions, construction types and materials, number of stories, use sector, economic value, and any others that may be needed to connect to the vulnerability module.
Vulnerability module: the vulnerability module of a probabilistic risk assessment consists of a set of probabilistic vulnerability curves which depict the expected behavior of an asset under a determined hazard. These curves relate hazard intensity to a level of damage, typically expressed through a percentage of the asset's value that is lost. To create these functions for individual assets that are required to be studied in detail, adequate and structure-specific engineering models must be built; [input specific modeling method according to specific hazard]. On the other hand, for the surrounding communities, which may comprise numerous assets, the exposure database shall be classified into general structural typologies (groupings), and existent vulnerability functions may be used.
Risk module: the risk module of a probabilistic risk assessment combines the hazard, exposure and vulnerability modules and computes losses in a probabilistic manner. The objective of a PRA lies in obtaining the complete universe of possible losses and their probability or frequency of occurrence. The sequence of the risk calculation is as follows: for each hazard scenario, the probability distribution of the loss is computed for each exposed asset, then the probability that the loss for this scenario exceeds a certain value is computed, then this is multiplied by the annual frequency of occurrence of the scenario, and finally the contribution of all scenarios is computed.
Risk results are usually depicted in what is called the loss exceedance curve (LEC), which contains all the necessary information on losses. From the LEC, a couple of metrics can be derived, which are usually used to express risk: the Average Annual Loss (AAL), Probable Maximum Loss (PML) and probabilities of exceeding certain losses in specific timeframes. Risk maps can be created, illustrating the geographic distribution of the AAL, in both absolute (economic losses) and relative (as a percentage of the exposed assets' value) terms, to visually identify areas at higher or lower risk.

9.2. The consulting firm must have experience in disaster risk assessments, [only for hydrometeorological hazards: climate modelling, climate change vulnerability assessments], [hazard] modeling, and statistical analysis. Having a local team member is a plus. At least one member of the team should have proven practical knowledge of the intervention area. The consultant team can be composed of any number of specialists as long as they combine at least the following experience:

- Project leader: At least 15 years of demonstrated professional experience in leading multidisciplinary groups in disaster risk assessments, [only for hydrometeorological hazards:

1 https://ir.lib.uwo.ca/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1027&context=wrrr
2 http://www.lboro.ac.uk/departments/sspgs/social-impact/climate-adaptation/

climate risks and climate change]. Master's degree in project management, engineering, administration, economics, finance, or related field.

- Disaster risk specialist: At least 10 years of demonstrated professional experience in conducting disaster risk analysis, [only for hydrometeorological hazards: specifically working with climate-related risks and climate change]. Proven experience in developing [hazard] models and conducting probabilistic [hazard] risk analyses. Proven command of probabilistic disaster risk methodologies and modeling platforms such as CAPRA, HAZUS or similar. Professional degree (preferably Master's) in civil or environmental engineering, geography, or similar.
- [Only for hydrometeorological hazards: Climate Modeler: University professional with a Master's degree in civil or environmental engineering, atmospheric or climate science, or related field.]
- [Hazard] Modeler: Professional with a Master's degree in engineering or similar, and at least 5 years of demonstrated experience in [hazard] modelling. [Input hazard-specific requirements].
- Local specialist: University professional with at least 10 years of proven working experience in the intervention area.

10. Supervision and Reporting

    10.1. (Describe the specific requirements: establish responsibilities for the technical requirements and approval of products.)

11. Schedule of Payments

    11.1. (Describe the schedule of payments according to products.)

Appendix J: Disaster Risk Management in Multiple Works Operations

During Identification Phase

PHASE 1

Step 1: Screening

- Classify each project included in the sample using the disaster and climate change risk questions in the toolkit.
- Using the maps: Ideally, if information on the projects included in the project sample is available and it is georeferenced, use it for the screening.
- Take the highest classification of the projects included in the sample to assign a classification to the entire operation. (The classification of the entire project is based on the highest classification of the project sample, like the environmental and social classification.)

Step 2: Criticality

- Review the initial classification made with the toolkit for projects included in the sample, analyzing their vulnerability and criticality.
- If more technical information (project scope, scale and design) on each project in the sample is available at this point, and any aspect of the classification needs to be reassessed, then use the additional information.
- Assess the criticality and vulnerability of each independent single infrastructure. For a system or network,[1] assess its criticality and redundancy, and determine the number of people served by the system. Refer to Step 2 of the Methodology for more information on how to assess single infrastructures or systems.

During Preparation of the POD

PHASE 2

Step 3: The Risk Narrative

- For multiple works, the narrative should include an explanation of why the entire operation has been assigned the classification. The risk narrative for multiple works should be based on the assessment conducted for the project sample. The risk narrative must provide details on the projects included in the sample that determine the entire classification of the operation. Justify the risk level given to each project classified as high or moderate-risk and provide details on which ones will need to go through a DRA (or equivalent) and a DRMP for which specific hazard.
- In addition, the risk narrative must contain a framework with guidelines on how the program will treat the rest of the projects not included in the sample. This will typically include a Disaster Risk Management Framework for the remaining projects not included in the sample.[2]

1 Systems include infrastructure that involves connectivity, such as transmission or distribution lines, potable water, or sanitation networks.

2 Typically, this includes the other 70 percent of projects. For multiple works operations, 30 percent of the projects should be included in the sample.

- Depending on their classification, some of the projects included in the sample might need to go to Step 4 – Qualitative Assessment, or even to Step 5 – Quantitative Risk Assessment. The risk narrative for multiple works must establish which projects in the sample need to move on to Step 4 and/or Step 5.
- If the overall operation has been classified as high disaster risk based on the categorization of the projects included in the sample,[3] this implies that the overall multiple works program allows the inclusion in the program of other high disaster risk projects.

Disaster Risk Management Framework

- The disaster risk management framework must set forth the rules (including exclusion criteria, in terms of disaster risk) for the risk classification and the assessment of the need for a risk assessment and mitigation measures following the Methodology. It could be included as part of the environmental and social management framework[4] or in the program's operating manual.

PHASE 3

Step 4: Workshop on Failure Analysis

- Step 3 must determine which projects will need to go to Step 4, a workshop with local and technical experts to identify failures, their causes, and solutions and formulate a plan of structural measures to reduce risks.
- For those projects that move to Step 4, the executing agency, the engineering team and a disaster risk and/or climate risk expert should participate in the workshop. In multiple works operations, it is essential that the municipality and relevant local agencies involved in the project in need of the workshop, as well as the community, participate in the workshop.

Step 5: Detailed Quantitative Analysis

- Step 5 applies to those projects of the sample for which a quantitative analysis has been deemed necessary.
- If any of the projects included in the sample already includes a detailed quantitative analysis, then other projects that are not part of the sample and require such analysis may go through one. It is important to keep this in mind when designing the disaster risk management framework.

Minimum Outline of a Disaster Risk Management Framework

1. Scope of projects to be financed by the operation.
2. Relevant legal and regulatory framework related to disaster risk, including building codes and other relevant standards for the sector or industry.
3. Eligibility criteria (including exclusion criteria).
4. Project Appraisal:
    - Project classification.
    - Risk assessment studies needed, according to the project classification.
    - Analysis, assessment, and approval.
5. Annexes.
6. Terms of reference for the preparation of disaster risk assessment and disaster risk management plan for moderate-risk projects, or both high-risk projects (including a detailed quantitative analysis): follow the examples of terms of reference included in the Methodology.

3 This follows the same logic as the environmental and social classification.

4 The environmental and social management framework is the instrument required to manage environmental, social, health, and safety aspects in a multiple works operation.

Appendix K: Drainage Characteristics

Wet Ponds

Wet ponds are constructed basins that have a permanent pool of water throughout the year (or at least throughout the wet season). Also called stormwater ponds, retention ponds, and wet extended detention ponds, they differ from constructed wetlands primarily in having a greater average depth. The primary removal mechanism is settling, as stormwater runoff resides in this pool. Limited pollutant uptake, particularly of nutrients, also occurs to some degree through biological activity in the pond.

Dry Extended Detention Basins

Also referred to as dry ponds, dry detention ponds, and dry extended detention ponds, dry extended detention basins are basins whose outlets have been designed to detain the stormwater runoff from a water quality design storm for some minimum time (typically 48 hours) to allow particles, trash, and associated pollutants to settle. Unlike wet ponds, these facilities do not have a large permanent pool. They can also be used to provide flood control by including additional flood detention storage. The primary purpose of most detention basins is flood control, but they can also be used to remove pollutants. Variations in design can vary this performance. For example, vegetated detention basins provide improved pollutant removal when compared to concrete basins. An optional micropool at the basin's outlet can be incorporated to increase performance of soluble pollutants.

Constructed Stormwater Wetlands

Like natural wetlands, constructed wetlands improve water quality through physicochemical and biological processes as water is temporarily stored. Specific unit processes include sedimentation, denitrification, and uptake. Consequently, the flow path through the wetland should be maximized to increase residence time and contact with vegetation, soil, and microbes. Very high sediment removal efficiencies have been reported for properly sized stormwater wetlands (50 to 80 percent reduction), with average effluent concentrations near 9 milligrams (mg) per liter (L) (Geosyntec Consultants, Inc. and Wright Water Engineers, Inc., 2012; Hathaway and Hunt, 2010). Subsequently, particle-bound metals are thought to be reduced as sediment falls out of suspension, and significant reduction of total copper, total cadmium, total lead, and total zinc is expected (although metals can dissociate from sediment and organic matter into solution under anaerobic conditions) (Geosyntec Consultants, Inc. and Wright Water Engineers, Inc., 2012; Newman and Pietro, 2001).

Bioretention Areas

Bioretention areas are landscaped, shallow depressions that capture and temporarily store stormwater runoff. Runoff is directed into the bioretention area and then filtered through the (often engineered) soil media. Bioretention areas usually consist of a pretreatment system, surface ponding area, mulch layer, and planting soil media. The depressed area is planted with small- to medium-sized vegetation, including trees, shrubs, and ground cover that can withstand urban environments and tolerate periodic inundation and dry periods. Plantings also provide habitat for beneficial pollinators and aesthetic benefits for stakeholders. They can also be customized to attract butterflies or particular bird species. Ponding areas can be designed to increase flow retention and flood control capacity.

Permeable Pavement

Permeable pavement is a durable, load-bearing paved surface with small voids or aggregate-filled joints that allow water to drain through to an aggregate reservoir. Stormwater stored in the reservoir layer can then infiltrate underlying soils or drain at a controlled rate via underdrains to other downstream stormwater control systems. Permeable pavement allows streets, parking lots, sidewalks, and other impervious covers to retain the infiltration capacity of underlying soils while maintaining the structural and functional features of the materials they replace.

Permeable pavement systems can be designed to operate as underground detention if the native soils do not have sufficient infiltration capacity, or if aquifer protection, hotspots, or adjacent structures preclude infiltration. Permeable pavement can be developed using modular paving systems (e.g., permeable interlocking concrete pavers, concrete grid pavers, or plastic grid systems) or poured-in-place solutions (e.g., pervious concrete or porous asphalt). Some pervious concrete systems can also be precast. In many cases, especially where space is limited, permeable pavement is a cost-effective solution relative to other practices because it doubles as both transportation infrastructure and a best management practice (BMP).

Cisterns and Rain Barrels

Cisterns and rain barrels are containers that capture rooftop runoff and store it for landscaping and other non-potable uses. With control of the timing and volume, the captured stormwater can be more effectively released for irrigation or alternative grey water uses between storm events. Rain barrels tend to be smaller systems that direct runoff through a downspout into a barrel that holds less than 100 gallons. Cisterns are larger systems that can be self-contained aboveground or belowground, are generally larger than 100 gallons, and can direct water from one or more downspouts. Belowground systems often require a pump for water removal.

Cisterns and rain barrels primarily provide control of stormwater volume; however, water quality improvements can be achieved when each are used with other BMPs such as bioretention areas. Permanently open outlets or operable valves can control water in cisterns or rain barrels depending on project specifications. Cisterns and rain barrels can be a useful method of reducing stormwater runoff volumes in urban areas where site constraints limit the use of other BMPs.

Green Roofs or Vegetated Roofs

Green roofs and vegetated roofs reduce runoff volume and rates by intercepting rainfall in a layer of rooftop growing media. Rainwater captured in rooftop media then evaporates or is transpired by plants back into the atmosphere. Rainwater in excess of the media capacity is detained in a drainage layer before flowing to roof drains and downspouts. Green roofs are highly effective at reducing or eliminating rooftop runoff from small to medium storm events. They can be incorporated into new construction or added to existing buildings during renovation or re-roofing.

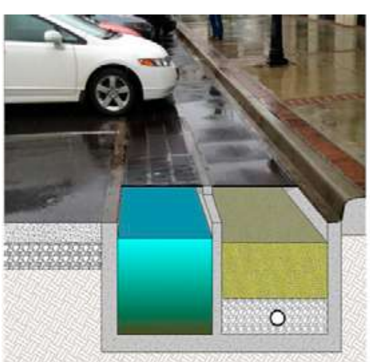
In addition to stormwater volume reduction, green roofs offer an array of benefits, including extended roof life span (due to additional sealing, liners, and insulation), improved building insulation and energy use, reduction of urban heat island effects, opportunities for recreation and rooftop gardening, noise attenuation, air quality improvement, bird and insect habitat, and aesthetics (Berndtsson, 2010; Getter and Rowe, 2006; Tolderlund, 2010). Green roofs can be designed as extensive, shallow-media systems or intensive, deep-media systems depending on the design goals, roof structural capacity, and available funding.

Tree Box Filter

A tree box filter is a concrete box containing porous soil media and vegetation that functions like a small bioretention area but is completely lined, must have an underdrain, and has one or more trees. Runoff is directed from surrounding impervious surfaces to the tree box filter where it percolates through the soil media to the underlying ground. If the runoff exceeds the design capacity of the tree box filter, the underdrain directs the excess to a storm drain or another device.

Tree box filters have been implemented around paved streets, parking lots, and buildings to provide initial stormwater detention and treatment of runoff. Such applications offer an ideal opportunity to minimize directly connected impervious areas in highly urbanized areas. In addition to stormwater management benefits, tree box filters provide on-site stormwater treatment options, green space, and natural aesthetics in tightly confined urban environments. Tree box filters are ideal for redevelopment or in ultra-urban settings and may be used as a pretreatment device.

Sand Filter



A sand filter is a treatment system used to remove particulates and solids from stormwater runoff by facilitating physical filtration. It is a flow-through system designed to improve water quality from impervious drainage areas by slowly filtering runoff through sedimentation and filtration chambers. With increased detention time, the sedimentation chamber allows larger particles to settle in the chamber. The filtration chamber removes pollutants and enhances water quality as the stormwater is strained through a layer of sand. The treated effluent is collected by underdrain piping and discharged to the existing stormwater collection system or another BMP. Sand filters can be used in areas with poor soil infiltration rates, where ground water concerns restrict the use of infiltration, or for high pollutant-loading areas.

Grassed Swales

Grassed swales are shallow, open vegetated channels designed to provide for nonerosive conveyance with a longer hydraulic residence time than traditional curbs and gutters. Grass swales provide limited pollutant removal by sedimentation and gravity separation. Properly designed grass swales are ideal when used adjacent to roadways or parking lots, where runoff from the impervious surfaces can be directed to the swale via sheet flow. Swales are effective for pretreatment of concentrated flows before discharge to a downstream BMP.