General Guidelines for the Development of Studies to Reduce Hydroclimatic Risks in Cities

Lessons learned from the Emerging and Sustainable Cities Initiative in face of the climate change challenge in Latin America and the Caribbean

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ABSTRACT
Urban conglomerates concentrate risks and opportunities for more than 80% of the population in Latin America and the Caribbean (LAC), and they constitute appropriate analysis units to conduct studies on natural disaster risks. This document provides guidelines to conduct quantitative and probability analyses of risks associated with hydroclimatic phenomena and climate change in cities: coastal, riverine and extreme pluvial flooding, hurricanes, winds, beach erosion, and urban drought. A large part of the methodology presented has been applied in the Emerging and Sustainable Cities Initiative (ESCI) of the Inter-American Development Bank - a pioneering program developed from 2011 to 2018. This document provides multiple practical examples taken from the work done as part of the above-mentioned initiative.
Building on the experience gathered over several years conducting disaster risk and climate change vulnerability analyses in emerging cities of the region, this document systematizes the lessons learned from these studies in a set of methodological guidelines that may help guide future studies, including a number of best practices for incorporating information from climate change scenarios.

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Executive summary —

Urban conglomerates concentrate risks and opportunities for more than 80% of the population in Latin America and the Caribbean (LAC), and they are appropriate analysis units to conduct studies on natural disaster risks. This document provides guidelines to conduct quantitative and probability analyses of risks associated with hydroclimatic hazards and climate change in cities: coastal, riverine and extreme pluvial flooding, hurricanes, winds, beach erosion, and urban drought.

A large part of the methodology presented has been applied in the Emerging and Sustainable Cities Initiative (ESCI) of the Inter-American Development Bank - a pioneering program developed from 2011 to 2018. This document provides multiple practical examples taken from the work done as part of the above-mentioned initiative.

Risk assessments start with the gathering of information available from different contexts, covering from climate and hydrology data to major socioeconomic variables, at the most detailed scale possible. It is also necessary to research the characteristics and effects of historical catastrophic events, as they provide useful information to calibrate and validate subsequent calculations. It is of the utmost importance to characterize not only the current and past climate, but also future climate – which is projected through the best tools available from the climate change science. In this regard, it is convenient to use estimations on a regional or even local scale, as opposed to the large-scale projections provided by the IPCC, as they lack the level of detail required for studies focused on cities. In addition, besides the fact that climate is considered a changing factor in risk studies, it is also necessary to consider urban growth scenarios, as future climate will also impact future cities. The development of urban growth scenarios does not follow well-established scientific laws, it is rather the result of each country's and region's historical process. Urban growth scenarios should be established by considering envelopes of potential pathways defined with the cooperation of specialists in the field.

Once the initial information has been gathered, the first step in risk studies is focused on quantifying hazards, that is, the physical phenomena that are capable of producing damage. This is undoubtedly the most technical part of the study, which requires a combination of statistical procedures and numerical models to solve the equations used to determine the matter and energy flows involved: precipitations (or an absence of precipitations), river flows, waves, wind, sediment transport, etc. A first classification of risk studies is usually based on the hypotheses applied to define uncertainty and the rate of occurrence of the sources of hazard (deterministic, pseudo-probabilistic, or fully probabilistic approach), as well as on the characteristics of the models used to extend those hazards (aggregated, distributed, 1D, 2D, or 3D models). The ultimate goal of the section on hazards is to obtain the probability of occurrence of the variable capable of producing damage in the physical space: for floods, maximum water depth and water velocity; for wind, peak speed at ground level; for coastal erosion, maximum shoreline retreat.

After characterizing a hazard, it is necessary to research into the characteristics of the other main component of risk: vulnerability. This concept comprises the characteristics of all the elements that can suffer damage from an extreme event: people, buildings, and all the elements that enable the normal operation of a city, that is, its transportation network, energy, water and communication infrastructures, schools, hospitals, etc. The first characteristic of all the entities that are potentially vulnerable to a hazard is their location in space; when a hazard coincides in space with elements that can potentially be damaged, then these elements are considered to be exposed, even if they do not actually get damaged. Exposure is a sine qua non condition for risk, it is the possibility that damage may occur in a certain place; the fact that damage may or may not materialize will depend on the properties of the exposed entity, notwithstanding its location. Vulnerability factors depend on the specific damage mechanism. For a house that is impacted by an accumulation of rainfall, vulnerability depends on the value of the goods and equipment located in the basement and on the ground floor, which are the places that can be flooded; on the other hand, when it comes to hurricane wind, vulnerability will depend on the material and the building typology of the roof and walls of the specific type of house. Specifically for people, the most relevant vulnerability factors are warning time, the existence of evacuation plans, and the proportion of children, elder people, and people with reduced mobility.

Once we have established the hazard and the relevant vulnerability factors for each hazards, we may define damage curves expressing the amount or proportion of damage associated with an extreme event in relation to the total value of the assets at risk. Also, by combining the damage from several events with different occurrence probabilities it is possible to calculate the annual average loss associated with a certain phenomenon. Risk results for a city are usually presented differentiating those that are economic in nature – and which can be therefore expressed in monetary terms as a replacement value (USD/ha) – from those that refer to the population, that is, the average number of people affected or displaced, injured, and dead. These damage parameters in absolute terms may in turn be presented in a non-dimensional way so that they can be compared across different cities or points in time: annual mean damage as a percentage of the GDP, or percentage of the population affected by natural disasters.

At this point, we will have a diagnosis of the situation in terms of hydroclimatic risks in a specific city and the evolution trends of such risks under the foreseen scenarios of urban growth and climate change. This diagnosis is useful by itself to prioritize investments by cities and allocate climate change adaptation resources, but does not provide any criteria regarding the most efficient measures to reduce risks. Based on the ESCI experience, a useful tool to bridge the gap between said diagnosis and a proposal of measures is to research into the risk construction mechanisms (RCMs) that are specific of each city. These mechanisms are defined as cause-effect chains that guide the production of risk in a specific urban context and include exogenous factors (that is, of a regional, national or even global scale) and local feedback loops. For floods – one of the most common risk types – the most usual RCMs have been identified by type of city, together with the most appropriate approach that must be followed by risk reduction programs in each case. This classification of cities intends to summarize – for practical purposes – some of the lessons learned in the risk studies conducted as part of the ESCI.

In general, any city subject to a certain level of risk will require a program of measures combining infrastructure and management interventions like awareness-raising, training, land planning, reforms of the legal and institutional framework, etc. When designing risk reduction works it is important – whenever possible – to prioritize measures inspired by the natural operation of the territory where the intervention is made, ideally using organic elements in flexible and adaptive arrangements. Ultimately, solutions that are viable for practical purposes are usually hybrid (a combination of green and traditional infrastructure), because land scarcity and the inherent nature of the urban space prevent the implementation of a wholly nature-based approach. It is critical to combine structural interventions with supplementary interventions at the social, institutional and regulatory level so as to guarantee not only risk mitigation in a specific area, but also the neutralization of the mechanism that has generated and will continue to generate it in other places.

After conducting the relevant studies, several alternatives to reduce risks in a specific case should be identified, and it is necessary to have tools to select the most appropriate one. There are two large types of methods to do this: the cost-benefit analysis and the multi-criteria techniques. In the first method, the benefits and potential drawbacks of each alternative are translated into monetary units taking into account their materialization over time and considering, like in any financial intervention, a time depreciation of cash flows based on the compound interest rule. As for the multi-criteria techniques, several scales for ranking the appropriateness of a measure can be introduced. They will not necessarily be quantitative, nor need they result from adopting a market price for all the factors involved. Both approaches have strengths and weaknesses that will be described in this document. The implementation of either approach – or a combination of both – will depend on the objectives sought in each case.

After many years of experience conducting disaster risk and climate change vulnerability analyses in emerging cities of the region, we consider it convenient to systematize the lessons learned from these studies in a set of methodological guidelines that may help guide future studies, including best practices on how to incorporate information from climate change scenarios. At the same time, it is also necessary to support a better identification of opportunities for investment in adaptation based on studies on climate change vulnerability and impacts (including water stress factors), since climate change is one of the main challenges faced by the cities of the region. This requires robust methodologies that are applicable considering the time and resources available when conducting urban planning in the region, which enable the identification of opportunities to invest in urban climate resilience and disaster risk management in the urban investment portfolios. We hope this document proves useful to cities and institutions facing these challenges. —

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Introduction —

With an urbanization rate of 80% - the highest in the developing world and foreseeably higher during the next decades – the cities in Latin America and the Caribbean are particularly vulnerable to the impacts of climate change, including natural disasters like floods and landslides, as well as slow-onset phenomena like a gradual increase in water shortage.

To face these challenges, the IDB has significantly increased its commitment to urban development through the creation of the Climate Change and Sustainable Development Sector (CSD), which integrates three pillars of urban resilience: urban development, environmental and disaster risk management, and climate change resilience.

After many years of experience conducting disaster risk and climate change vulnerability analyses in emerging cities of the region, including under the Emerging and Sustainable Cities Initiative (ESCI), we consider it appropriate to systematize the lessons learned from those studies in a set of methodological guidelines that may help guide future studies, including best practices on how to incorporate information from climate change scenarios.

The ESCI is a non-reimbursable technical assistance program executed from 2011 to 2018 by the Inter-American Development Bank, aimed at providing direct support to central and local governments in the development and execution of urban sustainability plans. The ESCI promoted the idea that well planned, comprehensive and cross-sectoral strategies for urban development can improve the standard of living and help achieve a more sustainable, resilient and inclusive future in emerging cities in Latin America and the Caribbean. For such purpose, the initiative used an operating methodology that is organized in two stages and five phases. The first stage starts with the execution of a rapid-evaluation diagnostic tool to identify the sustainability challenges of a city. Afterwards, the issues identified are prioritized through the application of different filters (environmental, economic, public opinion and the expertise of specialists in each sector) in order to identify the problems which represent the most critical challenges for the sustainability of a city. This stage ends with the formulation of an action plan which includes prioritized interventions and a set of strategies for their execution in the short, medium and long term. In the second stage, the execution phase starts with pre-investment studies for the prioritized interventions and the implementation of a citizen monitoring system.

The ESCI adopts a comprehensive and interdisciplinary approach to identify, organize and prioritize urban interventions to deal with the major challenges preventing the sustainable growth of emerging cities in Latin America and the Caribbean. This cross-cutting approach is based on three pillars: (i) environmental and climate change sustainability, (ii) urban sustainability, and (iii) fiscal sustainability and governance. Within the first pillar, the studies on risks generated by climate and geology-related events have proven to be key base studies for planning and guiding the growth of many cities. Floods, droughts, earthquakes, landslides and coastal erosion are affecting many cities in Latin America and the Caribbean, causing great economic and human damage and limiting their growth potential.

Many actions involving urban planning, transportation, or poverty reduction in slums are subject to risk factors usually referred to as “natural”. However, what can actually be considered as natural – though not even entirely – are hazards, since risks in the cities have been clearly built by humans when settling in areas that are exposed to hazards without adopting the necessary mitigation measures.

Climate change adds a complex and serious dimension to the risk production mechanisms that are appearing in many cities of this region. Natural phenomena like extreme rainfall, the El Niño phenomenon, and hurricanes are changing their patterns of occurrence, and science is not always capable of accurately predicting how or when such changes will affect a specific area in the medium and long term.

The purpose of this document is to present a set of experiences and offer recommendations for the undertaking of studies on hydroclimatic risks 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 other entities.

There are countless publications on hydroclimatic risks, many of which specifically addressing cities, edited by all kinds of national and international institutions. Some of them are technical in nature and focus on detailing procedures and methods for conducting quantitative studies, while others address the economic, social, or institutional side of disaster management. Save for certain exceptions, both types of works are strongly biased in terms of their approach. Technical publications largely adopt a physical-mathematical approach with a significant numerical and statistical component to quantify the uncertainty of results, which drives lay audiences away. The rest of publications focus on issues that can be only partly reduced to figures and numerical models, like the design of the appropriate legal and institutional framework to address a certain type of problems, the effective transfer of knowledge and technology to developing countries, risk reduction financing mechanisms, etc.

This document seeks to bridge the gap existing between disciplines and approaches, and to hybridize technical aspects with the approaches offered by social and positive sciences. To this end, the basic and most relevant aspects of the quantitative risk assessment techniques are presented in this document without using equations, in an accessible language and with practical examples; this way, we expect to draw the attention of social science experts and decision makers for them to gain basic knowledge of what they can expect from their fellow physicists and engineers in the context of risk studies. Additionally, we invite scientific-technical readers to look into the immense complexity of integrated risk and disaster management, which sometimes prevents the results of their studies from being translated into actual decisions and outcomes, as they blur into a reality with many more dimensions. As a more ambitious goal, this document will seek to prevent technical studies from falling into reductionism (as is often the case), even (or especially) when they involve a higher mathematical-statistical effort.

This document is, therefore, not a technical guide, nor is it aimed offering detailed calculation methodologies and protocols to specialists in charge of drawing up risk studies. With this in mind, we have – as far as possible – omitted formulas and technical language that would render this document inaccessible to a broad spectrum of readers. Its target audience are those responsible for planning, bidding or implementing risk-related plans and programs, as well as anyone whose activities are related to urban risks, that is, land-use planners, public servants, sociologists, and emergency managers. It is also expected to be useful to scientists and engineers willing to dig into how their work connects and links with other disciplines involved in risk diagnosis and reduction.

As any alternative proposal, this work faces many challenges, the most evident being the possibility of disappointing a majority of its potential readers – flood risk specialists will find that "their part" is too short and simplified, economists will see shortfalls and inaccuracies in the cost-benefit analysis, sociologists will find that the treatment of reflexivity and the theory of systems is biased, etc. In any case, we expect that readers searching for a general approach, but without intending to replace the experts on specific issues, appreciate this synthesis effort and the attempt to soften the boundaries between academic disciplines and professional approaches as a way to advance the study of risks.

The document is divided in seven chapters, as shown in the contents diagram in Figure 1. Chapters 1 to 4 describe methods and tools, which are predominantly technical and quantitative, to assess current and future risks affecting cities. They ultimately seek to establish the basis to diagnose risks in a city prior to addressing the analysis of mitigation measures – dealt with in Chapters 5 to 7. The second part of the document is less technical and prescriptive, considering that, although the diagnosis of urban risks may – up to a certain point – follow a pre-defined scheme, a viable and effective risk reduction program must be adjusted to the specific conditions of each city, which may vary enormously between countries, climates, and socio-cultural characteristics. Therefore, the second part of this document will include illustrative ideas and reflections that should be adapted to the context of each city.

Given the great amount of all kinds of material related to natural risks, this document does not intend to provide new methods or tools, but to select and arrange the most useful ones from a practical perspective, and offer them to those responsible for conducting risk studies in cities.

Finally, there are two recurring concepts in the document which label a great part of the lessons learned on risk management: uncertainty and cross-cutting nature. Both concepts determine the most important features that the professionals dedicated to reducing risks in the future must have: knowledge, flexibility, and capacity for dialogue.

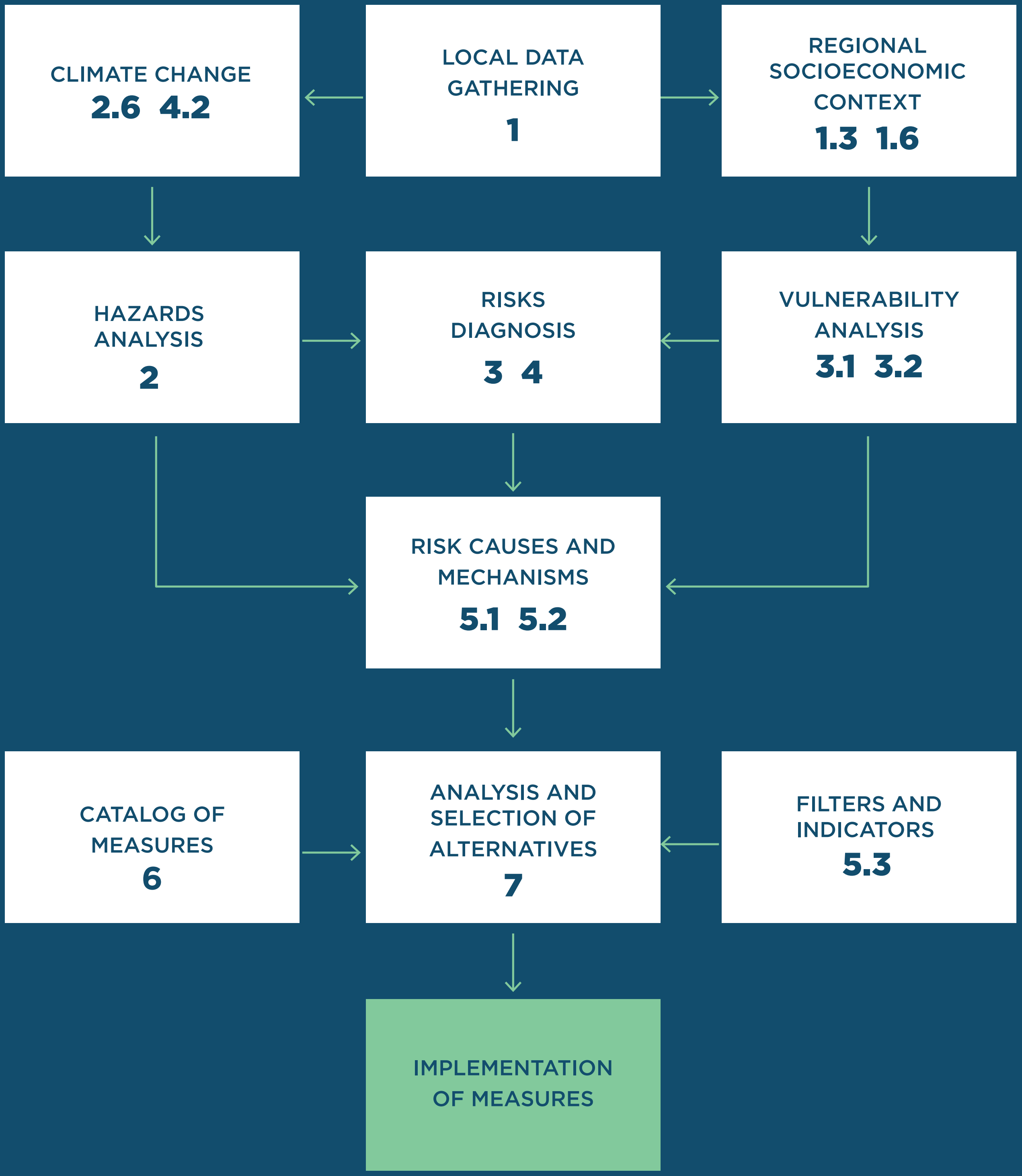

Figure 1 | Guiding map of contents of this document.

1

General framework and input data —

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1.1 The city as a risk analysis unit

Today, approximately 54% (4,000 million) of the world population lives in cities, compared to 43% (2,300 million) in 1990, according to a report of the United Nations (UN-Habitat, 2016). Everything indicates that this general trend will continue during the next decades, although with certain differences between regions.

Cities represent relatively compact geographic areas where the ecosystem functions and structure have been deeply transformed producing an intensification of materials and energy consumption (Forman 2008; Kulp and Strauss 2016). From a strictly bio-geographical perspective, urban areas are, to a greater or lesser extent, drains of resources produced in their area of influence, which manage to remain unbalanced with the outside thanks to the constant input of matter and energy.

This document will focus on the analysis and quantification of certain types of risks that mainly related to the atmospheric phenomena and water bodies (rivers, estuaries and coasts) interacting with them:

- Riverine flooding risks.
- Local rainfall flooding risks.
- Coastal flooding and sea level rise risks.
- Hurricane risks.
- Coastal erosion risks.
- Urban drought risks.

The first four are usually considered rapid-onset risks, while the last two are considered slow-onset risks. The study of these risks must include the urban area as well as the territories within its area of influence, as long as they determine the hazards or contribute non-replaceable resources. That is the case of a reservoir that stores water for urban consumption, a power plant, an airport, or a logistics center located outside a metropolitan area.

While the main focus of attention are risk studies within the urban environment, for each type of risk it will be analyzed whether it is necessary to conceive the city as an element linked to its influence area, or as an autonomous entity. As a general rule, the study of flooding and hurricane risks may or may not require a regional approach – it depends on each specific case -, whereas the study of coastal erosion and urban drought almost invariably requires the analysis of background processes (sediment budget in the first case, and water cycle quantification in the second case) that take place on a broader spatial scale than the urban patch itself. The consideration of the spatial scope of work according to each city and the selected risks of concern influences the collection of data, the determination of hazards, and the viability of the risk reduction proposals put forward.

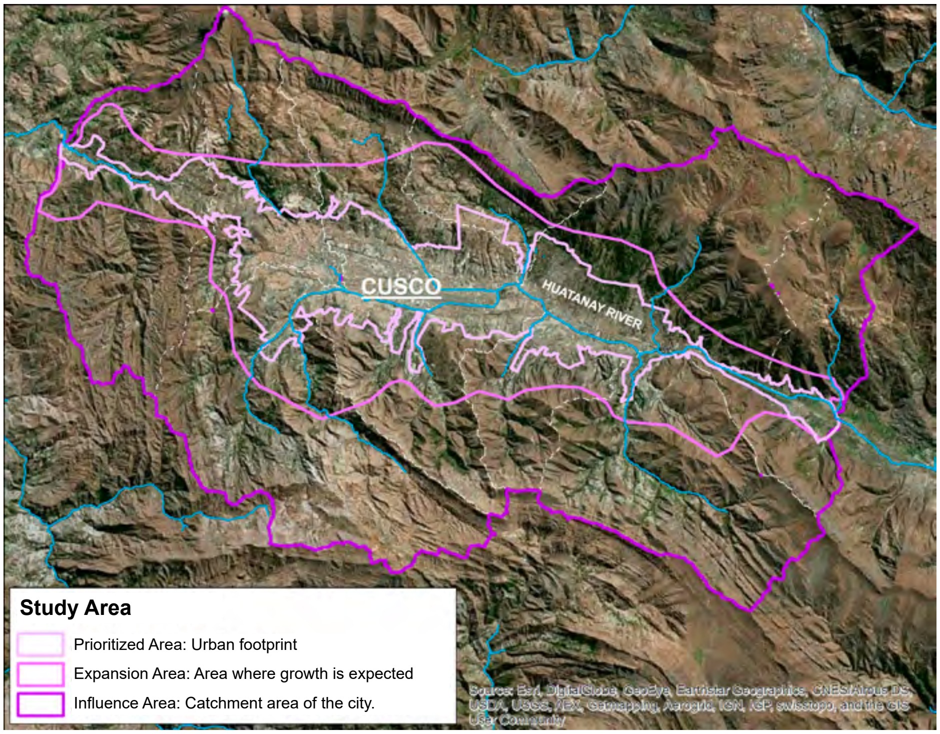
Notwithstanding the above considerations, the study of risks within the spatial scope of a city is appropriate, as it is within cities – rather than in their surroundings – that the largest proportion of the economic and human damage is produced, even if part of the causes of such damage originates outside the cities. Besides, because cities are usually not only geographic, but also administrative, legal and even cultural units, it is possible to more clearly identify the target of the studies (the municipality) and the legal framework for risk reduction measures (urban master plan, local ordinances, etc.). In general, in any study of the risks affecting cities it is convenient to determine three different areas as soon as possible:

1. **Prioritized Area:** it refers to the present urban area generally including the areas with urbanization projects in an advanced development phase. It represents the area where detailed results of damage in the present situation are going to be obtained and where these results are subject to calibration.

2. **Expansion Area:** it refers to the areas where short- or long-term urban growth is expected and where future risks can be estimated based on growth scenarios, always with a far higher degree of uncertainty than in the already consolidated areas.

3. **Influence Areas:** it refers to all the peri-urban areas, sometimes distant, where physical, social and economic processes interact in the definition of the present or future hazard. It is the case, for instance, of a basin of a river that passes through a city, the tributary basins of the reservoirs feeding water to such river basin, or a stretch of the riverbank acting as a source of sediments of another stretch.

In order to implement this initial zoning, it is important to previously know the risks to be studied, as well as the scale of the related physical processes. The amount and accuracy of the data to be collected on climate, territory and uses depend on the type of area at issue. Figure 2 shows an example of delimitation of the three areas in a flood risk study for Cusco, Peru.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 2 | Example of delimitation of the study area for flood hazard in Cusco, Peru.

1.2 Methodological and conceptual framework for risks assessment

Following a broadly accepted conceptual framework (Abhas et al., 2014), risk results from the temporal and spatial coincidence of a hazard and an entity (a living being or any physical or intangible element of the territory) capable of experiencing a loss of value, functionality or wellbeing, as a consequence of such hazard. Exposure is the binary feature reflecting such coincidence, whereas vulnerability gathers all the factors that explain the conversion of a hazard into damage (Fritzsche et al., 2014). Vulnerability is ultimately the characterization of certain properties of the exposed elements in terms of their potential to be affected or destroyed, and may have different dimensions: human (physical or psychological damage, death), economic (loss of value of the assets), or other type (e.g., environmental or heritage damage).

This scheme can be summarized in the pseudo-equation Risk = Hazard x Exposure x Vulnerability (Figure 3), which indicates that the total impact that may be produced by an event has an associated probability resulting from the combination of the probability of such event, the probability that it spatially affects the occupied areas and, finally, the probability that the assets and people exposed suffer damage (Plate, 2002). It should be noted that the exposure factor should be removed from this pseudo-equation when the hazard and the vulnerability are expressed as fields with their spatial variation (raster format), since the information on the point-to-point coincidence of the hazard and the vulnerability would be implied in such fields.

An alternative conceptual scheme that is compatible with the previous one to represent the generation of risk is based on the identification of the risk elements in a chain of components, with a stronger spatial component and in the form of a time sequence (Narayan et al., 2012):

SOURCE → PATHWAY → RECEPTOR → CONSEQUENCE

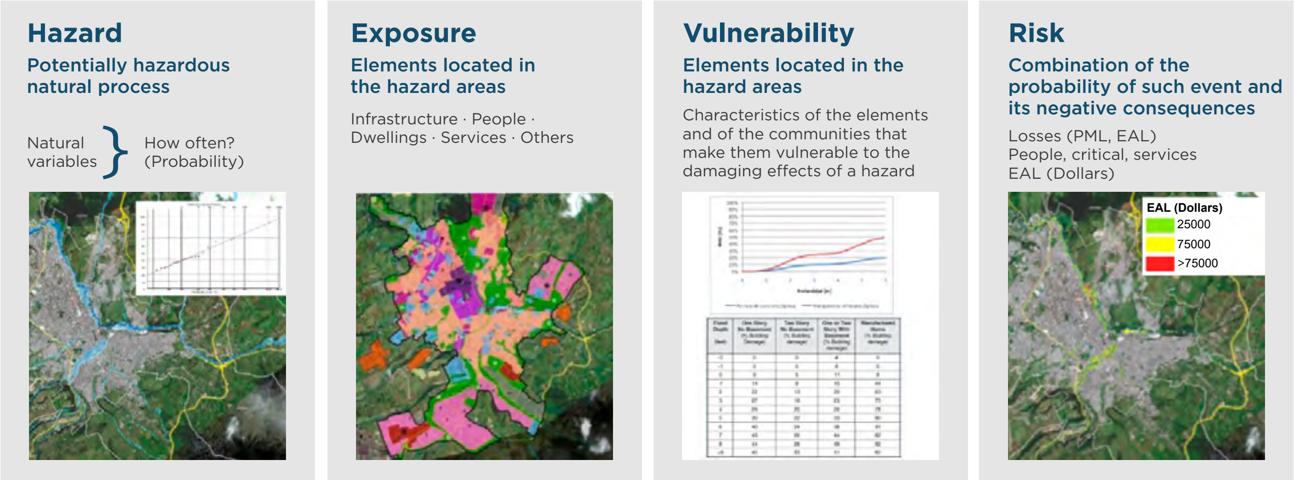


Figure 3 | Hazard-exposure-vulnerability-risk scheme.

With this approach, the risk is the quantification of consequences (in general, economic or human losses) with their associated probability resulting from a specific configuration of sources, pathways and receptors. In the case of coastal flooding, the sources would be the waves, the wind and the sea level, the pathway would be the beach and/or the defensive breakwater and, finally, the receptors would be the buildings and people behind such pathway.

1.2.1. Risk as a probabilistic phenomenon

Hydroclimatic risks depend on the combination of a set of factors that have a significant random component and thus cannot be expressed as a single deterministic value. We usually refer to a probabilistic risk assessment when the variability of any of the risk elements is taken into account and used to estimate the probability function of the expected effects or damage. Within the probabilistic risk studies, we can, for practical purposes, identify two main types of methodological approaches: the event analysis and the continuous simulation methods – called pseudo-probabilistic and fully-probabilistic approach, according to the IDB terminology.

Event-based approach (pseudo-probabilistic approach)

The event analysis is a widespread approach to address rapid-onset risks and, specifically, floods and hurricanes. It basically involves assessing the probability of occurrence of extreme events of a specific natural phenomenon characterized by one or more representative parameters, which are assigned a certain probability of occurrence.

Most of the studies on rapid onset-risks, like floods and hurricanes, are based on the characterization of extreme events (annual maximum events or events exceeding a predefined threshold). The concept of event varies according to the type of risk analyzed, as shown on Table 1. As it can be observed, events are characterized by different hydro-meteorological variables, which would a priori require the application of multivariate extremal probability functions. This is inevitable in certain cases:

Multi-source problem: It happens when many partially related or even independent physical processes produce the same type of hazard with a similar importance. For example, in the city of Belize, floods can occur due to a combination of strong local rainfall, the overflowing of the main river due to rainfall in the river basin, and sea level rise.

Multi-risk problem: Hurricanes, for instance, simultaneously produce sea level rise, heavy rainfall and extreme winds. The sea and the rain cause flood damage, whereas the wind causes damage from dragging and from the impact of projectiles. However, the combined damage cannot be obtained independently, since there is no additive effect (water can modify the damage associated with the wind, and vice versa, and both phenomena cannot damage the same asset twice).

In general, a multivariate problem is statistically more complex and requires more data on extreme events, which are not usually available. In most practical studies, it is often decided to select a dominant variable and to assign a deterministic value to the other variables. In this way, the dominant variable probability is transmitted throughout the risk calculation and is inherited by the final damage results. In the case of riverine flooding, the dominant variable is the total rainfall, and for the rest of the dependent variables, fixed values are adopted based on technical criteria:

- Rainfall duration: average time of concentration of the watershed.
- Time structure of the rainfall: synthetic hyetograph.
- Spatial structure: homogeneous field with an areal reduction coefficient.
- Preexisting humidity status: soil at 90% of its saturation humidity (or similar).

HAZARD	EVENT	DEPENDENT VARIABLES	DOMINANT VARIABLE
RIVERINE FLOODING	Riverine flooding	Total rainfall Duration Time-space structure of the rainfall Preexisting humidity of the watershed	Total rainfall
PLUVIAL FLOODING	Rainstorm	Total rainfall Duration Shape of the Hyetograph	Total rainfall
COASTAL FLOODING	Coastal storm	Maximum waves level (height, period and direction) Maximum sea level Duration of the event	Maximum wave height or maximum sea level
HURRICANE (WIND ONLY)	Windstorm	Maximum intensity of the wind Duration Evolution in time of the wind intensity	Maximum wind intensity

Table 1 | Characterization of the calculation events associated with the analyzed rapid-onset risks.

The event-based risk assessment provides discrete points of the probability function of the damage curve – for example, the value of the economic damage D_i associated with events with a return period of 5, 10, 20, 50, 100 and 500 years. The return period is nothing but an alternative way to present probabilities: an event with a T-year return period has a probability of exceedance of 1/T and a probability of non-exceedance of 1-1/T.

From there, the complete curve can be interpolated, either by using a well-known analytic function or in an empirical way. The value of the Annual Average Loss (AAL) – or the pure risk premium – results from adding the damage from the individual events weighted by their probability of occurrence:

$$AAL=\sum_{i=1}^{n}\frac{D_i}{T_i}$$

Where D_i and T_i are the damage and the return period associated with each calculated i event. The AAL is a fundamental indicator of the risk level to which a territory or city is exposed (generally expressed in a dimensionless manner, see section 5.3), and it is also useful for the cost-benefit analysis of risk reduction measures (section 6), since it provides the average recurrent saving derived from a certain action, as a difference between the average damage before and after carrying out such action.

Continuous simulation approach (fully-probabilistic approach)

The definition of the concept of event and its separation from the rest of ordinary situations is useful to facilitate the calculation and post-processing of results, but requires several hypotheses and is not appropriate for certain types of problems. Slow-onset risks, like hydrological droughts or, in part, coastal erosions, cannot be characterized through a reduced number of specific extreme events, since they tend to be linked to longer-term processes where the system's memory becomes relevant.

With today's computing capacity, it is increasingly possible to represent the complete sequence of a certain phenomenon without having to preselect the periods of interest. In the case of riverine flood risks, if there is a sufficiently long series of rainfall, it is not necessary to select certain storm events, as it is possible to obtain a continuous simulation of the complete flow series, turn it into a series of levels and even transform those levels into damage (fully-probabilistic approach, versus the pseudo-probabilistic approach that involves analyzing a number of discrete events with an associated probability). Note that this procedure implies adopting fewer hypotheses than in the pseudo-probabilistic approach, since certain factors like the form of hyetographs or the preexisting humidity of the soil would be integrated as internal variables of the simulation.

The main limitation of the continuous approach is the availability of series of input variables that are reliable, long and representative of all the types of extreme situations. Historical series of re-analysis from models, as well as satellite data on a global scale, are progressively making up for this limitation. Moreover, progress has been made in the development of models for the generation of synthetic series of physical variables, calibrated by instrument series. In some cases, with this approach, thousands of years of input data can be generated to characterize a specific phenomenon, including the effects of correlation with other factors, persistence, hyper-annual variability, etc. In general, the fully probabilistic approach is applied when there is enough data to characterize the uncertainty of all the parameters involved and to avoid selecting representative discrete events for multivariate processes, where there is not a single dominant variable. Box 1 shows an example of this type of approach, where thousands of synthetic hurricanes are produced to determine the combined probability of wind, rain and storm surge in a specific point. Section 3.8 includes a supplementary analysis on the statistical procedure of risk studies in terms of the quantification of uncertainty.

BOX 1 —

Types of climate and characterization of the hurricanes regime under climate change in Campeche (Mexico).

Problem

During the past years, the municipality of Campeche has been affected by numerous tropical depressions with catastrophic consequences. Some of these events, like Gilberto in 1988, Opan and Roxana in 1995, Isidore in 2002, and Dean in 2007, caused significant human and economic losses. Their low probability of occurrence and the uncertainty over their intensity and spatial distribution under climate change makes it very difficult to adequately characterize the real risk that they pose.

Methodology

The methodology applied combines statistical selection and classification techniques, as well as parametric and numerical models to simulate the different processes derived from tropical cyclones. Generally, these processes are wind, rainfall, waves and storm surge. The purpose is to generate spatial maps of return periods for each of these processes, for both current weather conditions and different climate change scenarios.

The first step is to select the historical tropical cyclones that have affected Campeche in the past, to then generate thousands of synthetic tracks associated with them (Nakajo, S., et al., 2014). The synthetic events are generated in order to increase the size of the initial sample, thus exploring situations that are different from those occurred during the historic period considered.

Once the synthetic tracks were generated, hybrid, statistical and dynamic downscaling was applied to model wind and flood – the latter as an effect of the combined action of rainfall, waves and storm surges. Through statistic selection and classification techniques (statistical downscaling), a number of cyclones that are representative of the complete sample have been selected in order to reduce the computational cost that would result from numerically modelling the different dynamics for all the events (dynamic downscaling). For each of the selected events, parametric models have been used to model the wind (Vortex model, Holland, G.J., 1980) and the rainfall (R-Clipper, Tuleya, R.E., et al., 2007). In turn, the wind fields feed the hydrodynamic numerical models with the purpose of simulating the waves and storm surges associated with such events. The next figure shows an example of the simulated spatial fields for wind, rainfall, waves and storm surge for a specific instant during tropical cyclone Gilbert (1988). The waves, storm surge and rainfall fields will in turn feed a hydrodynamic flooding model (e.g., RFSM-EDA or LISFLOOD) to reproduce the maximum flood for each of the selected events.

Through statistical techniques, maps of maximum flood, wind and rainfall have been rebuilt for the rest of the events (observed and synthetic). As a result, spatial maps for flood return periods have been generated, and wind and rainfall return period values have been calculated for the current climate.

With the purpose of including the effects of climate change in the methodology, the historic period has been broken down into a series of synoptic patterns of the sea surface temperature (SST) that represent all the existing weather types in such period; each of these weather types has a concrete associated cyclonic activity.

Next, the change in the probability of occurrence of each of the weather types for future climate has been calculated using the results of the global circulation models (GCM) of the CMIP5. Finally, through Montecarlo techniques, series of thousands of years of tropical cyclones have been generated for the different climate change scenarios.

Consequently, for future climate, flood return period spatial maps have been defined and the values of the return periods of the wind and rainfall variables have been established for the different climate change scenarios and horizon periods. The flood maps under future climate take into account the corresponding value of the sea level rise. The description of the complete methodology, including a probabilistic analysis of the risk, can be found at Izaguirre et al. (2017).

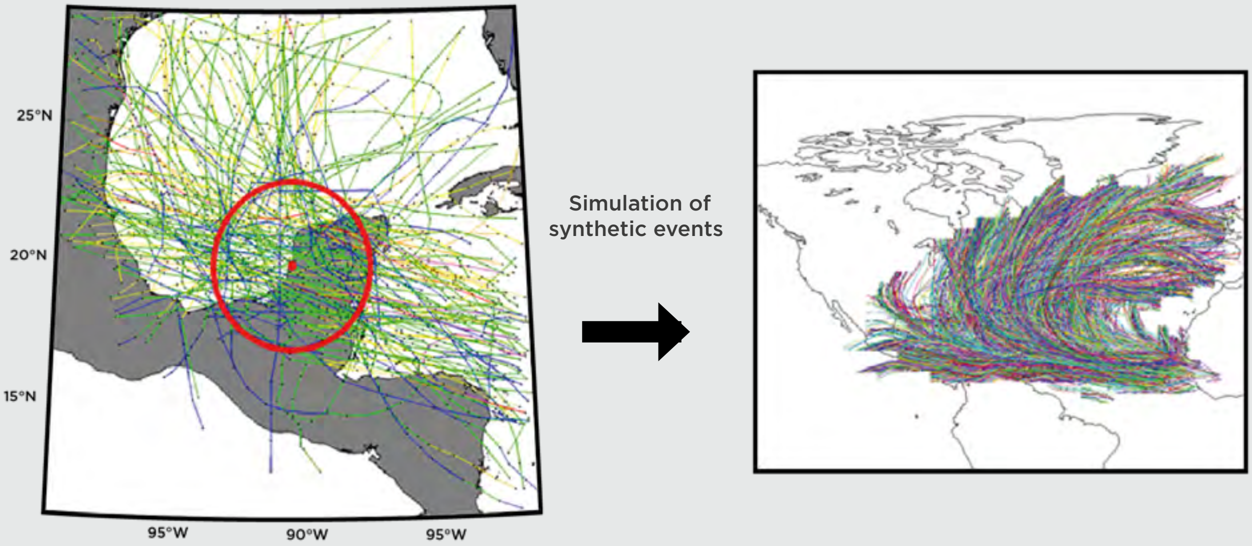
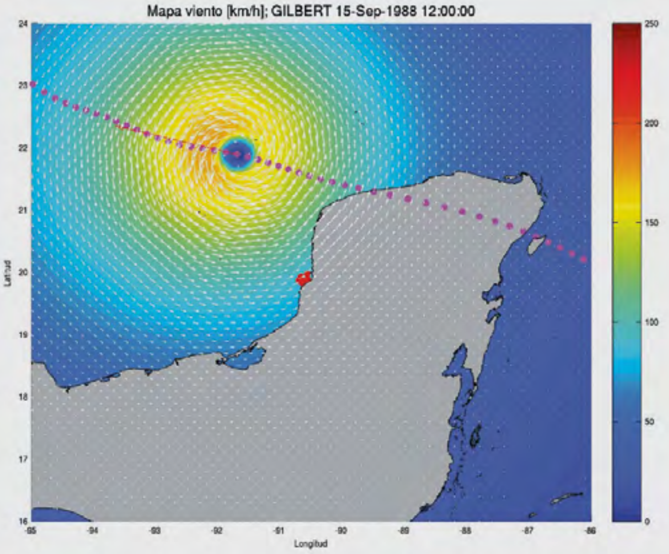


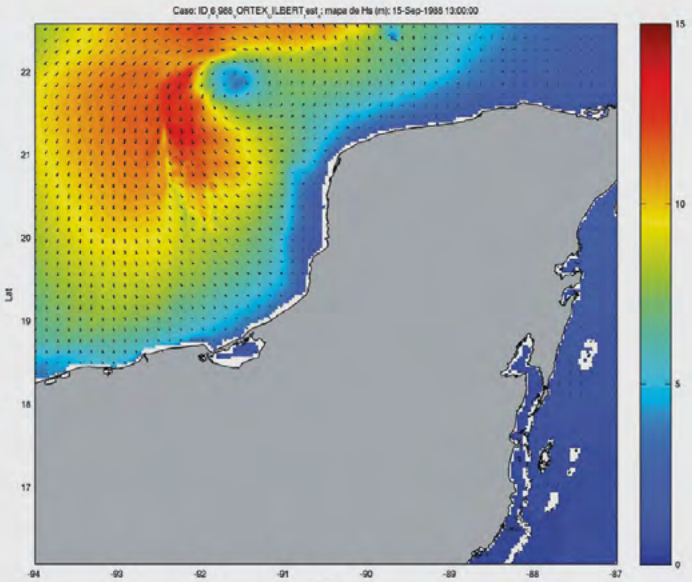
Figure 4 | The figure on the left shows tropical storms that passed less than 300km away from Campeche from 1950 to the present. The figure on the right shows the thousands of synthetic events simulated from the historic events.

Results

As outputs from this methodology, flood return period spatial maps for the current and future climate have been generated (next figure). Precipitation Intensity-Duration-Frequency curves (IDF) and wind speed return period values have also been calculated. Figure 8 shows an example of flood spatial maps for the 10 and 100-year return periods under the RCP4.5 scenario and for a time horizon centered in the year 2050.

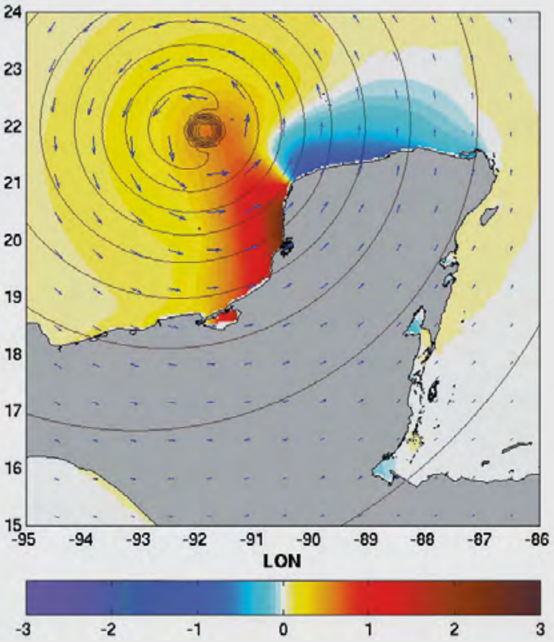


Wind fields
Hydromet-Rankine Vortex model

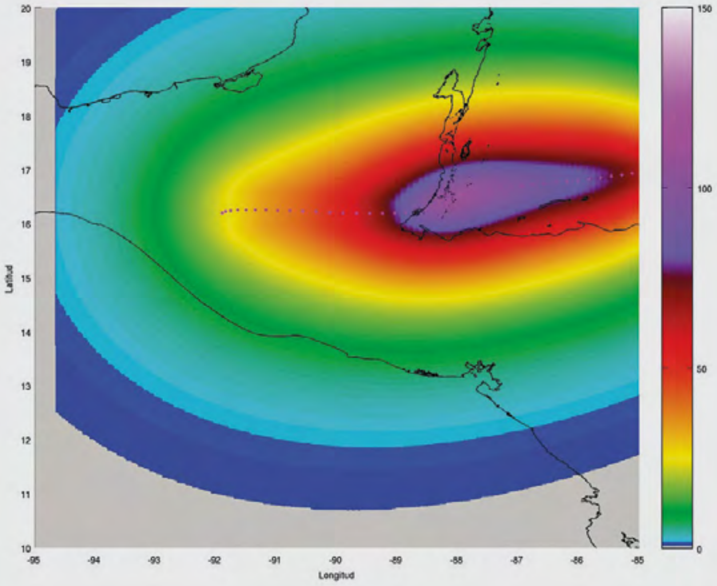


Wave fields
SWAN model

Figure 5 | Spatial fields for wind, wave, storm surge and rainfall for a specific instant during tropical cyclone Gilbert in 1988.



Storm surge fields
H2D

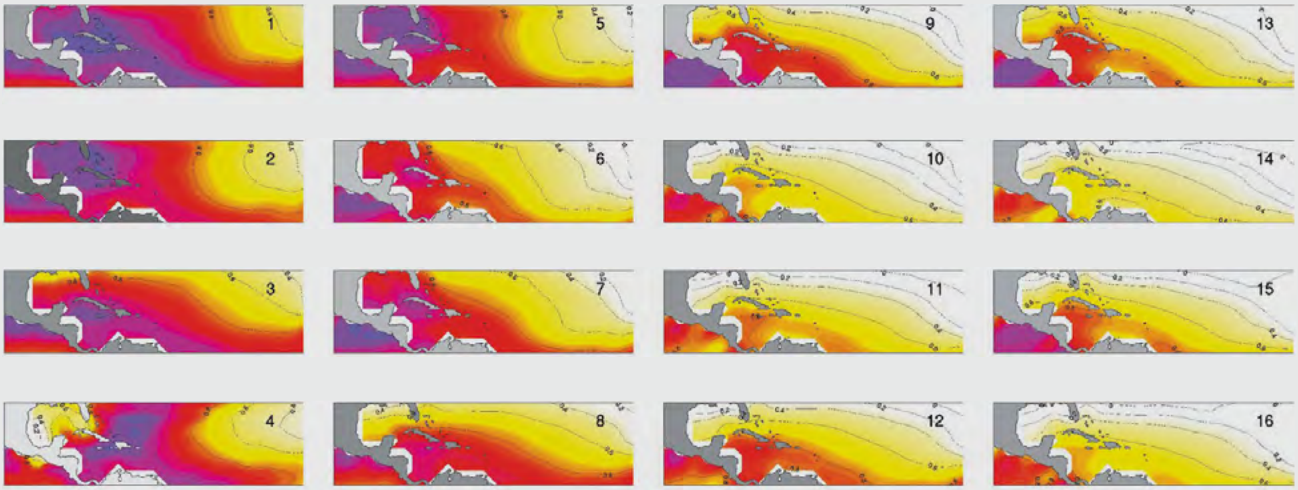


Rainfall fields
R-Clipper mode

Figure 5 | Spatial fields for wind, wave, storm surge and rainfall for a specific instant during tropical cyclone Gilbert in 1988.

WEATHER TYPES

SST



CYCLONIC ACTIVITY

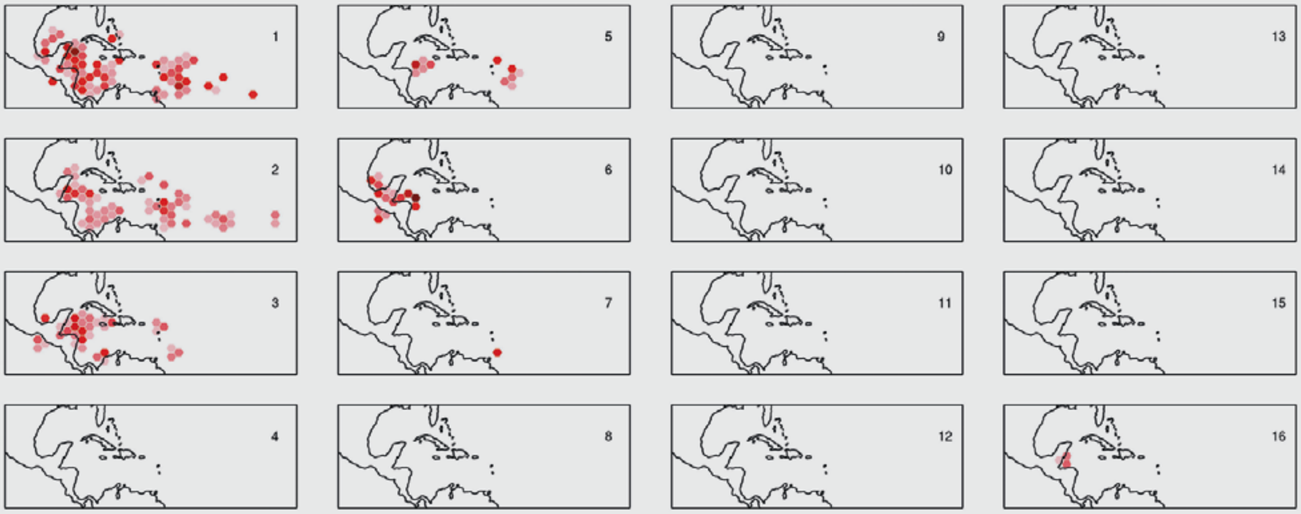
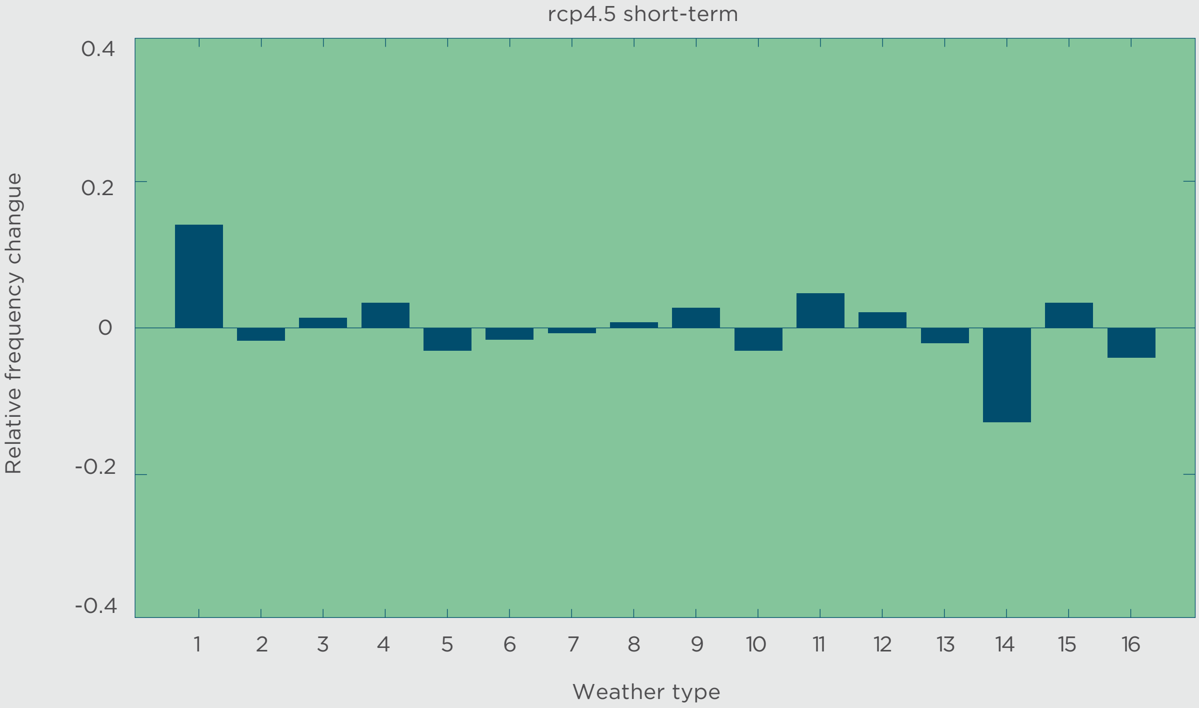


Figure 6 | The figure above shows the classification in 16 weather types of the sea surface temperature in the North Atlantic. The figure below shows the associated cyclonic activity.

Associated cyclonic activity.



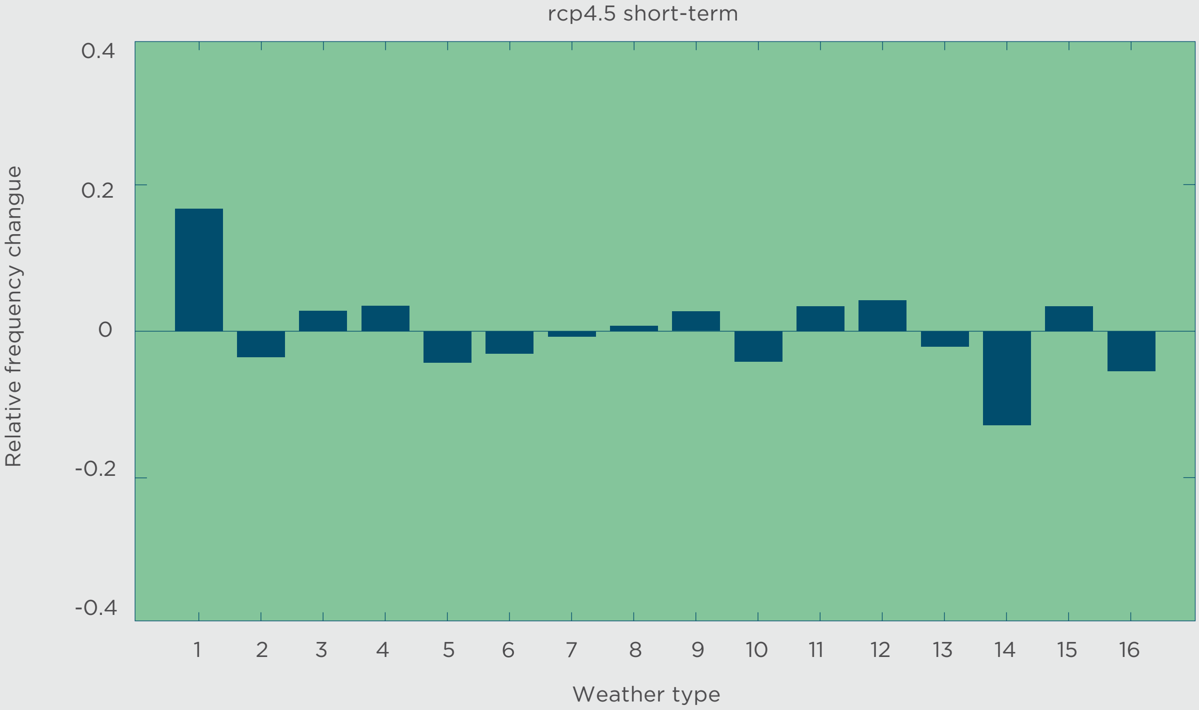
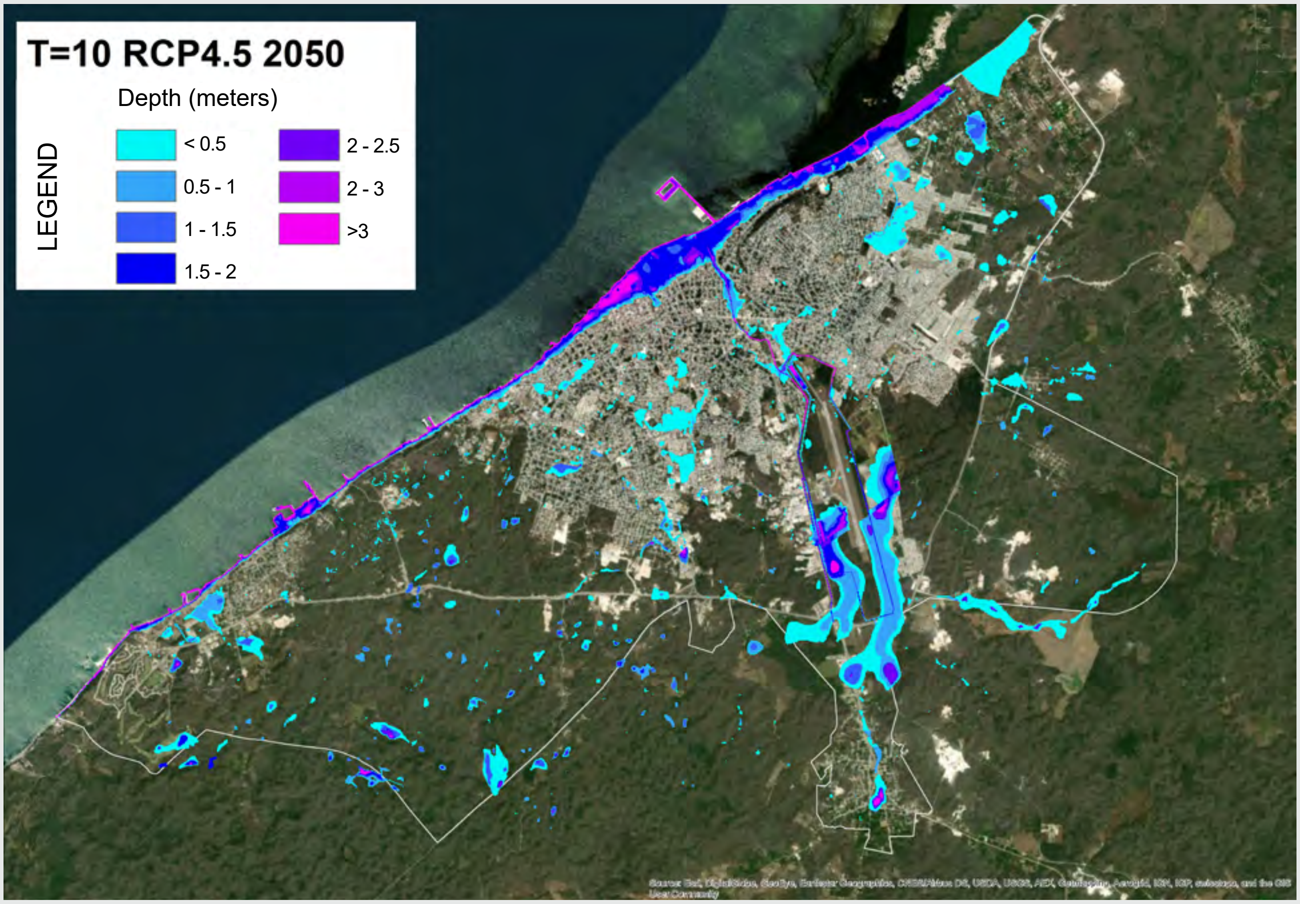


Figure 7 | Change in the probability of occurrence of each of the 16 weather types and of the RCP 4.5 climate change scenarios. The figure shows two horizon periods, a mid-term period centered in 2050 and a long-term period centered in 2085.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 8 | Flood spatial maps for the 10-year return period under RCP4.5 and for the time horizon centered in 2050.

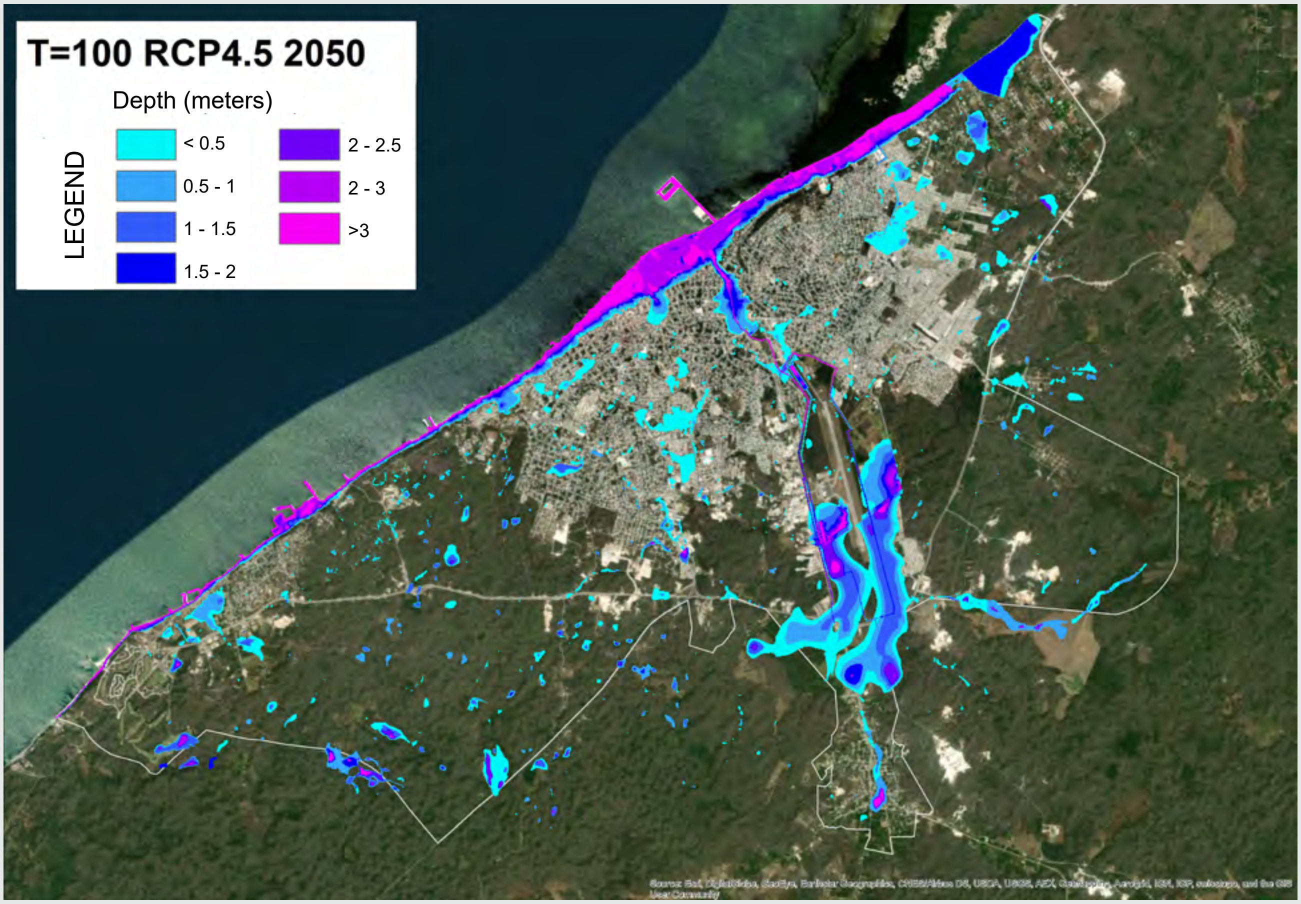


Figure 8 | Flood spatial maps for the 100-year return period under RCP4.5 and for the time horizon centered in 2050.

1.2.2 City scenarios in risk studies

As shown in the base studies conducted under the ESCI of the Inter-American Development Bank, the assessment of the risks affecting cities should not only focus on determining damage in the present situation, but also try to analyze the evolution trends of such risks. From a mechanistic approach, and therefore inspired in Newtonian physics, the characterization of a city from the risks point of view implies acknowledging two variables: its position (present status) and its velocity or rate of change, represented by one or many future scenarios. Just with a knowledge of the present situation it would be impossible to determine the possible pathways of a system, and therefore to plan any kind of intervention to try to modify them.

The real processes of risk evolution in cities, characterized through risk construction mechanisms (see section 5.1 in this document), are very complex and hard to model. However, as a first approach, and adopting a simplifying and reductionist method, the definition of future scenarios to analyze risks in cities requires two basic tasks that can be addressed, under certain hypotheses, in a relatively disconnected way: the characterization of future climate and the evolution of the urban patch with its influence area.

Characterization of future climate

Climate change on a global scale and its manifestation on a local scale is one of the most relevant and complex issues currently faced by scientists and practitioners in any field of reality. There is clear evidence that foreseeable changes in fundamental physic variables – such as temperatures (of the sea and air), sea level, and rainfall – will in the long term (2070-2100) have a profound effect in the ways of life and in the risk level to which all beings, including humans, will be exposed.

In the context of this document, it is of the highest interest to know how the rainfall regime, riverine flow, winds, waves and the sea level will change in a specific area in the not-too-distant future (2020-2040). Notwithstanding the scientific effort made during the last decades in terms of the characterization of the atmosphere-ocean processes and their changes, the impact mechanisms and the available adaptation and/or mitigation measures, the climate conditions to which a given city will be exposed in 20 to 30 years are still largely a mystery. General Circulation Models (GCMs) and their regional version (Regional Climate Models - RCMs) do not have sufficient spatial and temporal resolution to accurately characterize hazards to a scale of a few kilometers (1-10 km); besides, in certain climate variables like rainfall and, particularly, in more dynamic areas of the Earth like the Tropics, models present significant discrepancies in their long-term projections. Many of the LAC cities are located in tropical areas and are subject to two types of phenomena that resist numerical modeling: teleconnections (specially ENSO, commonly known as the El Niño) and tropical cyclones. These science limitations, which are expected to be resolved in the next decades, should not downplay the analysis of the effects of climate change as part of the planning undertaken in all spheres of activity, or inhibit a response from politicians and practitioners to one of the issues that could strongly influence the economic and human development of the region. In fact, the existing uncertainty combined with an informed knowledge of the issues at stake in every case should lead to the application of the precautionary principle and to the design of sector-specific strategies that are adjustable and flexible in the light of a changing world.

Changing the spatial scale from hundreds of kilometers (the GCM scale) to the scale of a city (a few kilometers) is a key task in the study of the risks that affect cities. At the same time, it is often necessary to have an estimation of the maximum values of a certain variable (e.g., rainfall) in a shorter period of time (hours) than the one provided by the models (days). Therefore, one of the most characteristic challenges in the studies analyzing the potential effect of climate change in the cities is the spatial and temporal downscaling of the existing estimations.

The specific procedures to downscale climate model projections will be outlined in two sections of this document: on one side, the projection of extreme phenomena, particularly rainfall, will be included in the context of the analysis of hazards related to events (section 2.6) and, on the other side, the calculation of the future mean precipitation regime or its derived stream flows, will be included in the context of urban drought risks (section 4.2) where it is more directly applied. This separation relates to material differences in the amount and quality of the information available to characterize the future mean precipitation regime and the extreme behavior of the different climate variables, which affects the reliability of GCM projections and, ultimately, the available methods to interpolate them. Additionally, the selection of the most suitable downscaling method depends on the purpose of the analysis, that is, on the type of risk reduction measure under analysis (structural, management, financial, etc.). Broadly speaking, there are two main types of downscaling methods: those based on solving the fundamental equations of processes with higher discretization (dynamic methods), and those using statistical methods calibrated with local data, not based on physics (statistical methods).

Another distinctive aspect of the analysis of climate change in the cities is the relatively short time horizon (normally 2020-2040) for which projections are required. In general, GCM outputs tend to be consistent and qualitatively similar (at least as regards temperature variations) for a longer horizon (typically 2070-2100), when roughly stable concentrations of greenhouse gasses are reached in the atmosphere, depending on the global emissions scenario or RCP (Representative Concentration Pathway) considered. The mid term is halfway between variability and climate change itself; although there is less uncertainty associated with the selection of RCPs, there is increased uncertainty over the modelling of physical processes.

Evolution of the urban patch and its influence area

In order to define the different scenarios of evolution of the urban patch, it is important to understand the patterns and mechanisms governing such growth, including those planned and included in plans that are in effect and under development, as well as those that have actually materialized over the last decades. A dual approach is therefore recommended: on one side, studying urban growth and the dominant processes as completed historical events and, on the other side, studying the evolution of the patterns and guidelines included in the different waves of territorial planning, including the current planning cycle and that under development.

As a practical and operative solution to the analysis of future scenarios, the studies under the ESCI consider a reduced number of growth scenarios which are as different as possible, characterized for two time horizons (e.g., 15 and 30 years here from). By adopting a minimum of three scenarios, it is possible to approximately represent an upper and a lower envelope, as well as a mid-point evolution of the possible future pathways of a city in relation to each analyzed risk:

1. Trend urban growth scenario

This scenario envisages future cities assuming that their recent risk construction patterns and mechanisms continue to operate and remain stable; this scenario involves either no interventions, or moderate interventions based on observed historical patterns. The typical premises of this scenario in LAC cities are high demographic growth, low – but not zero – public investment in infrastructure, and a predominantly reactive attitude towards risks. In this context, distressed areas tend to see a deterioration in their condition, and favored areas will continue to improve. In many cases, this scenario is equivalent to an unfavorable (although seldom worst-case) evolution hypothesis, as an upper risk envelope; however, in many cities where recent risk reduction measures have been adopted, it is incorrect to consider the trend scenario as unfavorable, and it should be rather assimilated to a mid-point or even smart scenario (see the sections below). If that is the case, the trend scenario category should be changed for the worst-case scenario category, in order to reasonably cover the whole range of potential developments.

2. Smart urban growth scenario

This scenario combines sustainable urban planning measures with actions to eliminate risks or reduce them to an acceptable level. The concept of urban sustainability and the acceptable risk criterion are not set as such, but are often determined in each case based on scales taken from cities with similar characteristics (size, geography, and climate) in developed countries. In any case, the smart scenario quantifies the reasonably reachable conditions if a rational urban growth model with sufficient resources to undertake the necessary risk reduction measures is followed. The degree of idealism that can be introduced in this scenario, and therefore the actual probability of its materialization, depend on technicians in charge of drawing up and supervising each study. In general, it is more interesting to propose this scenario as an optimistic but feasible development opportunity for a city taking into account its particular baseline conditions, than as a theoretical and unfeasible dream.

3. Intermediate urban growth scenario

It is heuristically defined based on the two preceding extreme scenarios, combining a set of intervention measures with other historical factors that remain unchanged and that can adversely affect the evolution of risks. It is a probabilistic and pragmatic scenario, halfway between the trend-pessimistic and the smart scenario.

The smart scenario and, to a lesser extent, the intermediate scenario involve risk reduction and urban planning actions, which will be addressed in section 6 further below. In order to compare the different scenarios in terms of effectiveness, different techniques can be applied (see section 7), including the cost-benefit analysis. Figure 9 shows an example of the procedure followed to assess human risk in the city of Quetzaltenango in Guatemala for the scenarios considered for that city: present, trend and smart, for the 2050 horizon.

When combining the possible trends of climate evolution, which determine the sources of hazards, with the possible trends of evolution of the urban patch, it is possible to quantify future damage in the same way as in the present situation, following a procedure like the one described in the following sections. However, this possibility to quantify future damage, based on analyzing urban and climate evolution almost independently, has certain limitations that should be borne in mind when interpreting and establishing the degree of reliability of the results obtained. Apart from the high level of uncertainty affecting both the future climate projection component and the evolution of the urban patch (see section 3.8), urban development depends to a certain extent (according to each city) on the evolution of risks, which, in turn, depend on urban evolution. Therefore, working on independent hypotheses of climate and urbanism evolution to afterwards combine them in a given year-horizon without analyzing their dynamic co-evolution is very reductionist (see section 5 for a more cross-cutting approach). Bearing this in mind, it is reasonable to regard the assessment of future risks in a city more as a prospection or exploration effort that stimulates reflection and public debate, than as a predictive act.

It should be noted that the concept of mitigation (equivalent to reduction) as used in this document is related to the sphere of disaster risk management, and not to climate change – where mitigation refers to measures aimed at reducing greenhouse gas emissions.

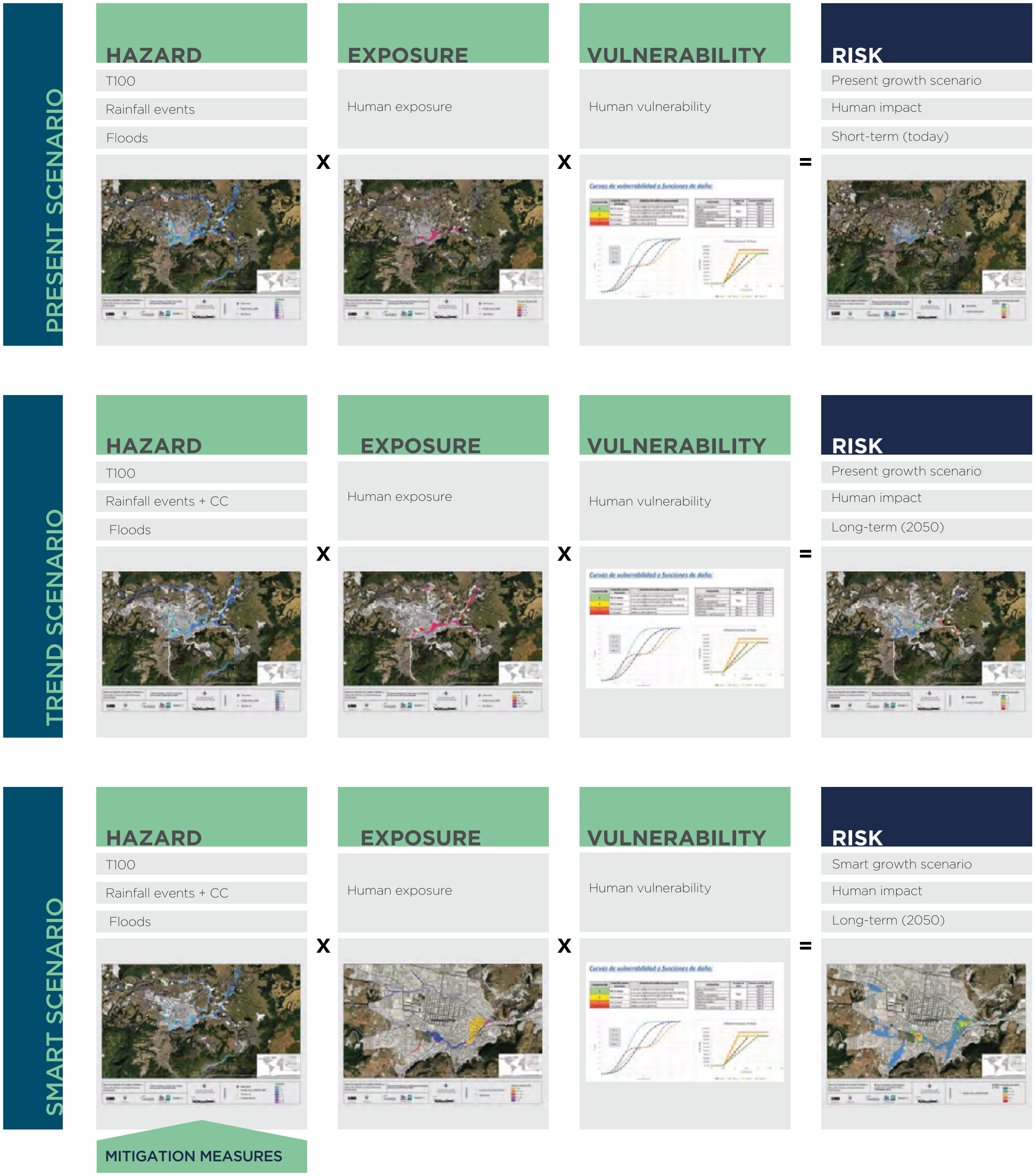


Figure 9 | Illustrative structure of a human risks assessment for the current scenario and the two growth scenarios considered (trend and smart) in Quetzaltenango, Guatemala.

1.3 Input data collection

1.3.1 Topographic and physical soil characterization data

The topographic data required to conduct risk studies depends on the hazard under study. Tables 2 and 3 show the necessary information on altimetry and physical characterization of the soil, according to the category of the study area, for different hazards.

Flood risk studies may, for the previously defined analysis of the influence area, require certain higher-scale (lower detail) topographic data to characterize river basins and their hydrological behavior, whereas prioritized and expansion areas require high-resolution topography, including bathymetry for adjacent river, estuarial or coastal areas. Generally speaking, the topographic data used in the analysis of the influence area has a 10 to 30-meter cell spatial resolution and is usually available from national mapping agencies (geographic or mapping institutes), or from global altimetry databases. Its accuracy varies between regions and depends on the data source. The following are some of the global altimetry databases available at the time this document was drawn up: ASTER, SRTM, IFSAR and TanDEM-X (see Sampson, Smith, Bates, Neal, & Trigg, 2016).

Detailed topography comes from conventional topographic surveys, flights generating stereoscopic imaging, and flights with LIDAR sensors. In all cases, fieldwork is necessary to calibrate the results of the data from airborne sensors. Obtaining detailed topography of the prioritized and expansion areas using these procedures is usually an expensive and time-consuming task. An intermediate solution applied in the market for some years now has been to generate topographic data with intermediate resolution and quality (between LIDAR and the global databases) based on high-resolution satellite images and field support. There are many companies and entities offering this service at a competitive price, although the accuracy of the results should be verified in each case. An acceptable resolution for a detailed topography in this type of studies is between 1 and 5 m (pixel size).

In coastal flood studies, it is necessary to obtain not only the topography of the emerged areas, but also the bathymetry of the coastal strip, since it affects the waves and water levels in the coastline, which will ultimately determine the flooding of the inland areas.

In order to assess the risks from extreme winds, if there are orographic features (in both the prioritized and the expansion or influence area), it is important to analyze the effect of topography in the spatial variations of the wind, although such analysis does not generally require a high-resolution topography. If the land is even, with no nearby orographic features, having a DTM may not be necessary, assuming a homogeneous wind field as a work hypothesis.

CALCULATION CONSIDERATIONS

Notwithstanding the source of the topographic data, floods in urban areas are highly influenced by the presence of singular elements such as walls, embankments, linear-works fillings, drains, catchment sewers, etc. Usually, the exact position and geometry of these elements are not correctly shown in the digital terrain models (DTM), even in detailed DMTs, which makes it necessary to introduce all or at least the most relevant ones manually. The generation of specific DTMs for hydraulic modeling by combining information provided by companies specialized in topography with real data of local infrastructure is a key task in flood risks analysis, in which no efforts should be spared since it has a great impact on the quality of results. It is important to point out that in order to conduct hydraulic modeling of a stretch of river or estuary, it is also necessary to know the depth of the submerged areas, which information is not usually included in the available DTMs.

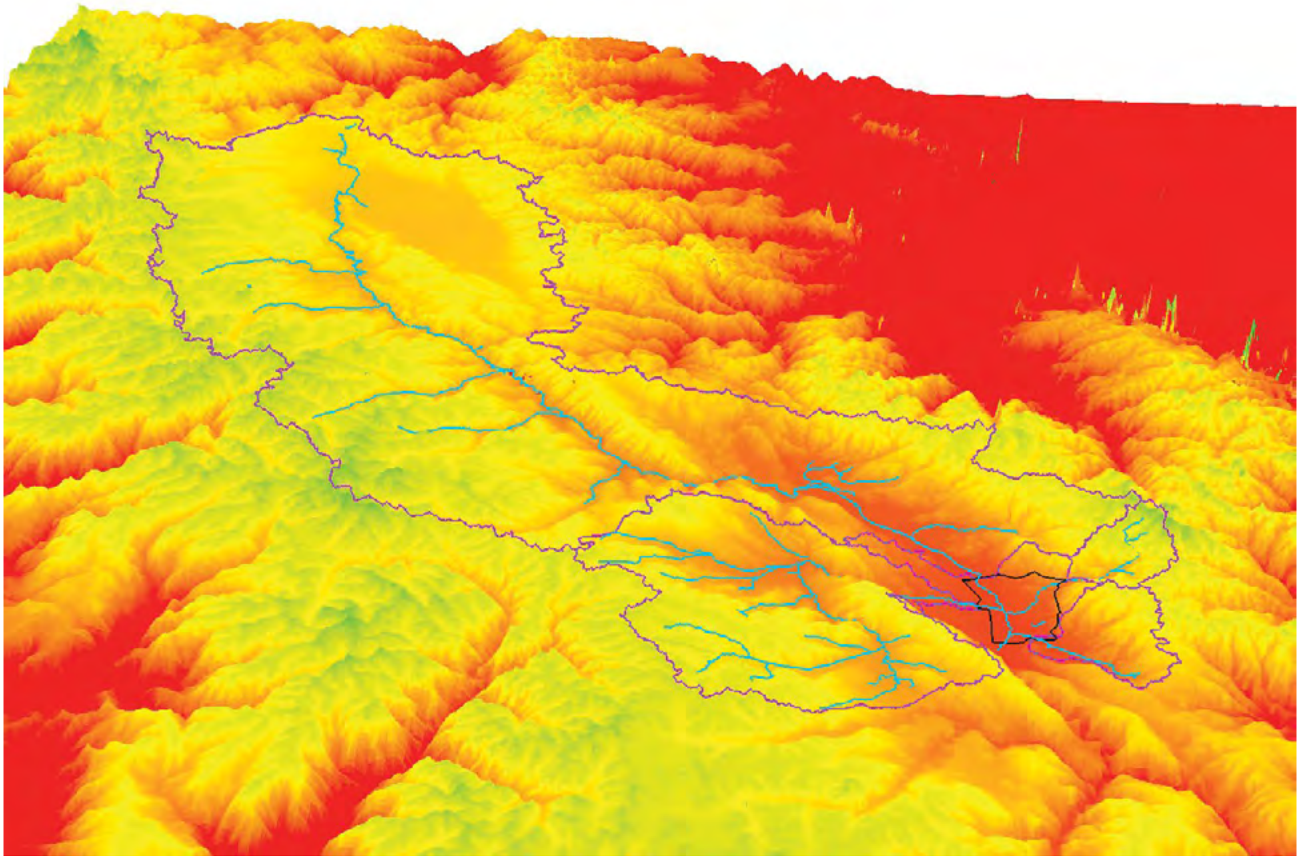


Figure 10 | Example of an DTM from ASTER with a resolution of 30x30 m used for the influence area in Huancayo, Peru.

Apart from requiring data on land elevation (Table 2), flood and wind risk studies require a physical characterization of the land and soil, including information on the physical roughness of the land surface represented through some type of coefficient, generally Manning or Chezy. Inside water bodies, such roughness is linked to the bed type materials (clay, sand, gravel) and the transportation regime (that determines the forms of the bottom, such as ripples, dunes, etc.) whereas in the emerged urban areas it depends, not only on the materials, but also on the density and distribution of the blocks of buildings.

The characterization of sediments, with their associated granulometric curve, is particularly important when studying coastal erosion risk, where morphological processes and the equilibrium configurations largely depend on the type of sediments together with the marine climate. In this type of studies, it is also particularly important to collect historical data not only on bathymetry and coastline position, but also on the dates of construction of maritime works and on the evolution of the type of sediment in a specific sector.

RISK	PRIORITIZED AREA	GROWTH AREA	INFLUENCE AREA
RIVERINE FLOOD	Detailed topography and bathymetry. Definition of defense works and existing drains (typology, standard section and elevations).	Detailed topography and bathymetry.	Low-resolution topography of river basins.
PLUVIAL FLOOD	Detailed topography. Definition of the main urban drain works, with its elevations and standard sections.	Detailed topography.	Not applicable.
COASTAL FLOOD	Detailed topography and bathymetry. Definition of the standard section and elevation of defense and protection works.	Detailed topography and bathymetry.	General Bathymetry. Historical evolution of coastline.
HURRICANE (JUST WIND)	Low-resolution topography in places with orographic variations that can induce significant spatial alterations in the patterns of the wind.	Low-resolution topography in places with orographic variations that can induce significant spatial alterations in the patterns of the wind.	
COASTAL EROSION	Detailed topography. Definition of the standard section and elevation of defense and protection works.		General Bathymetry. Historical evolution of coastline.

Table 2 | Topographic data required for risk studies.

RISK	PRIORITIZED AREA	GROWTH AREA	INFLUENCE AREA
RIVERINE FLOOD	Characterization of the hydraulic roughness of the territory. Particle size distribution of the river bottom.	Assessment of the future hydraulic roughness of the territory.	Characterization of the hydrologic properties of the soil. Storage capacity, permeability, curve number or similar, etc.
PLUVIAL FLOOD	Characterization of the infiltration and storage properties of the soil. Equivalent hydraulic roughness.	Assessment of the future infiltration and storage properties of the soil. Equivalent hydraulic roughness.	Not applicable.
COASTAL FLOOD	Characterization of the hydraulic roughness of the territory. Coastal particle size distribution.	Assessment of the future hydraulic roughness of the territory.	
HURRICANE (JUST WIND)	Characterization of the equivalent roughness of the land cover including the density and height of buildings.	Characterization of the equivalent roughness of the land cover including the density and height of buildings.	Characterization of the equivalent roughness of the land cover on a macro scale.
COASTAL EROSION	Characterization of the particle size distribution on beaches and seabeds by sectors.	Characterization of the particle size distribution on beaches and seabeds by sectors.	General bathymetry. Historical evolution of the coastline.

Table 3 | Data on the physical characterization of the territory in risk studies.

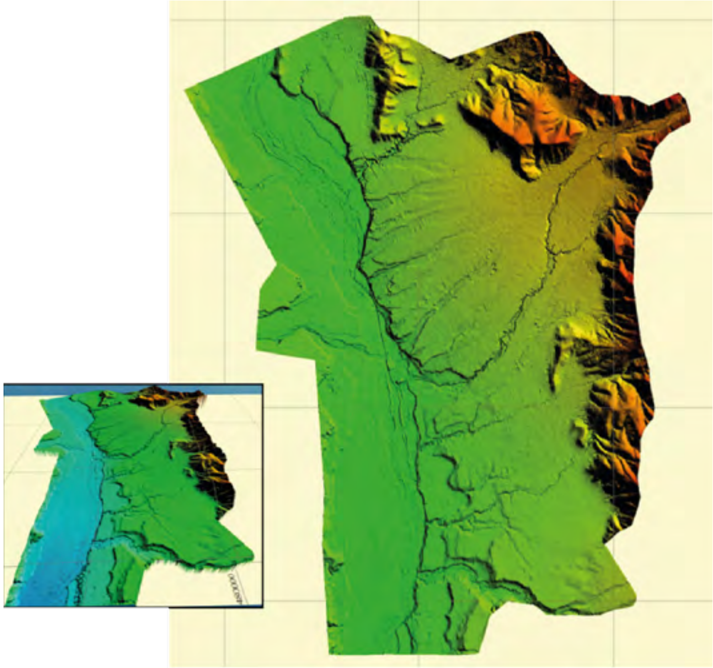


Figure 11 | Example of an MDT with a resolution of 2x2 m made from stereo-pairs used for the prioritized and expansion areas of Huancayo, Peru.

1.3.2. Collection of hydroclimatic and historical events data

Just like with topographic and physical soil characterization data, the hydroclimatic data necessary to conduct a risk study depend on the hazard under study. Table 4 shows different hydroclimatic variables for which it is advisable to collect data in order to characterize each of the hazards included in this document. Among those variables, some are dominant and essential to assess an actual hazard (see Table 1) and others are useful to calibrate the partial outputs of the models used in the process.

The common practice is to gather all instrument data on hydroclimatic variables at the beginning of a project, then make a quality control, and end with the selection of time series of different variables that are going to be used to calculate the related hazards. It is important to take into account that this data is the starting point to characterize a hazard and, therefore, the selection is of the essence in risk studies, especially in the case of the dominant variable. The selection process requires expert judgement and essentially depends on the duration and resolution of the time series, as well as on the reliability of the source or measuring system.

In many cases, the time series of data are short or have a high percentage of gaps. A simple and commonly used solution is to use satellite data from global and local databases of climate variables (precipitation, temperature, wind, etc.) and calibrate them with the available instrument data. Climate models provide information on all the atmospheric variables at different calculation levels. In the case of precipitation, which is one of the most used variables in the characterization of the different hazards, it should be noted that global and regional models usually capture it incorrectly. In this case, calibration with instrumental data is essential. An example of this is the satellite data from TRMM (Tropical Rainfall Measuring Mission), which has been used in many IDB studies, but which if not calibrated tends to inflate the values measured.

The gathering of data on historical events has two main functions in this type of studies. In the first place, it is very useful as a means for learning in the early phases of diagnosis and prioritization of studies what are the most important risks affecting a city. During this initial research, key aspects of past catastrophic events – such as recurrence periods, human and material damage, responsiveness, indirect damage, etc. – are taken into consideration.

In the second place, historic catastrophes are used to calibrate and validate quantitative risk calculation models based on the analysis of the available data, obtained from both measuring instruments and human witnesses (see section 3.7). In this sense, depending on the available information, it is possible to validate the hazard calculation procedure (e.g., the flooded area and maximum levels reached during a flooding event; see section 2), as well as the economic damage (e.g., the value of the destroyed and affected houses) and human damage (e.g., deceased, missing, injured, affected and evacuated people).

CALCULATION CONSIDERATIONS

It is advisable to use multiple regression techniques to establish relationships between the atmospheric patterns (pressure fields, geopotential height, temperature, etc.) and the instrument measures of the climate variables (rainfall, temperature, humidity, etc.) since the relationships obtained through regression may serve to transform the values obtained from models into values equivalent to instrument measures. Therefore, these relationships may be used to adjust and improve the projections of climate models in future scenarios.

RISK	HYDROCLIMATIC VARIABLES
RIVERINE FLOOD	- Daily or hourly accumulated rainfall. - Historical river flow data
PLUVIAL FLOOD	- Accumulated rainfall on an hourly or lower scale - Historical flow data
COASTAL FLOOD	- Waves in undefined depths (wave height, period, direction) - Sea level (astronomic tide + meteorological tide) - Wind regime
HURRICANE (JUST WIND)	- Wind speed and direction
COASTAL EROSION	- Waves in undefined depths (wave height, period, direction) - Sea level (astronomic tide + meteorological tide)
URBAN DROUGHT	- Daily or hourly accumulated rainfall. - Historical river flow data - Potential average evapotranspiration - Temperature

Table 4 | Hydroclimatic data recommended for the study of different hazards.

1.3.3. Socioeconomic data and urban information

Up to this point, all the information gathering has been focused on the calculation of the hazard, as it will be described in chapter 2. However, risks result from the combination of such hazard and a receptor, whose vulnerability features determine the generation of damage. Therefore, it is important to characterize the main features of the elements exposed to a certain risk, in order to assess their vulnerability. There is a large variety of features shaping vulnerability in a broad sense, some of which can be quantified whereas others cannot (i.e. those related to psychological, social, and cultural aspects). This document will focus on a quantitative approach to vulnerability factors, which will shorten and simplify the gathering of related information. There follows a summary of the main aspects necessary to apply the methodology that will be described in sections 3 and 4.

a. Inventory and characterization of buildings.

In order to assess potential damage deriving from a flood, hurricane or erosion process, it is necessary to know, on the available scale (individually or by blocks), the characteristics of the buildings that form the urban layout as regards structural typology, height, predominant use and replacement value. According to the IDB's accepted terminology, it is equivalent to the so-called individual assets and aggregated assets, with the latter also including a spatial individualization option and a spatial aggregation option.

b. Population density.

In order to determine the human component of damage, it is necessary to understand the average spatial distribution of population, as well as any additional information related to mobility patterns (factors that modify static population according to the time of the day, weekends, specific events, etc.). The starting point for this information is the population census carried out by municipalities, which in certain cases will be outdated and will require some adjustments to reflect the current situation. It should be noted that in many cities the number of people in certain sectors at rush hours is higher than the censed population, because the official census does not include certain categories (displaced people, immigrants) and due to pendular movements produced between urban centers and periurban areas, which are sometimes tens of kilometers away. For the same reasons, the actual population in some residential areas during working hours is lower than the one indicated by the census.

c. Inventory and characterization of critical infrastructure.

In addition to the characterization of general use buildings, including dwellings, it is convenient to identify, locate and characterize the buildings and centers of specific use such as: educational centers (day cares, schools, universities), hospitals and nursing homes, shelter areas, critical transport elements (stations, interchanges, bridges, highways, main roads, etc.) shopping malls, markets, fire stations, police stations, key energy facilities, etc. The information related to this type of facilities, referred to in this document as critical facilities, will be relevant to assess not only direct damage but also the potential systemic and differed effects associated with a certain hazard (see section 3.4).

d. Urban planning and expected urban growth.

Considering that risks studies not only refer to the present situation, but also seek to assess future trends, it is important to understand the growth patterns of cities, including those planned and included in plans that are in effect and under development, as well as those that have actually materialized over the last decades. A dual approach is therefore recommended: on one side, studying urban growth and the dominant processes as completed historical events and, on the other side, studying the evolution of the patterns and guidelines included in the different waves of territorial planning, including the current planning cycle (possibly with its new land use plan under development and processing). Discrepancies between the reality and successive land use plans usually provide valuable information to identify and characterize risk construction mechanisms, as discussed further below (see section 5).

All the information associated with the preceding four categories may be introduced in a cartographic database consisting of the following types of elements:

1. **Polygons representing basic working units**, generally blocks or urban sectors, whose basic characteristics are: structural typology and dominant materials, average height of buildings, average building density (percentage of constructed area considering the total area of the polygon), percentage of uses (residential, commercial, offices), replacement value of the buildings (in monetary units, usually USD, per m2) and census population associated with such polygon. If there is information, supplementary characteristics such as the ratio of children and elderly people, the average income of the population and any other variable that could give information regarding physical and human vulnerability can be added.

CALCULATION CONSIDERATIONS

It must be verified that the three types of polygons in which the urban space is divided do not overlap, and that the building densities are assessed consistently with the criteria used in defining such polygons. For example, if the polygons do not cover the urban space completely (because they do not include roads, or parks, or sports facilities) the building ratios will be higher than if the total space is included. The overlapping of sector or block polygons with critical infrastructure is incorrect, since it implies reckoning the damage twice (as conventional building and as critical infrastructure), although in the case of small facilities the mistake is insignificant. Finally, a common mistake with significant practical consequences is delimiting an urban polygon overlapping it with a river channel. In this case, the equivalent population of the overlapping area will have a high fatality ratio, without this resulting from a real situation, but from a GIS error.

2. **Polygons that represent the expected expansion areas in the city**, including not only their geographical demarcation, but also the basic characteristics of the new areas: main uses, building density, average height and typology of buildings, etc. It is convenient to clearly distinguish between potential expansion areas and areas that are already consolidated or under construction.

3. **Polygons representing the so-called critical infrastructures**. The main characteristics associated with these infrastructures are the type of infrastructure and all those parameters that are useful to quantify their importance within the urban sub-system to which they belong (see section 3.4).

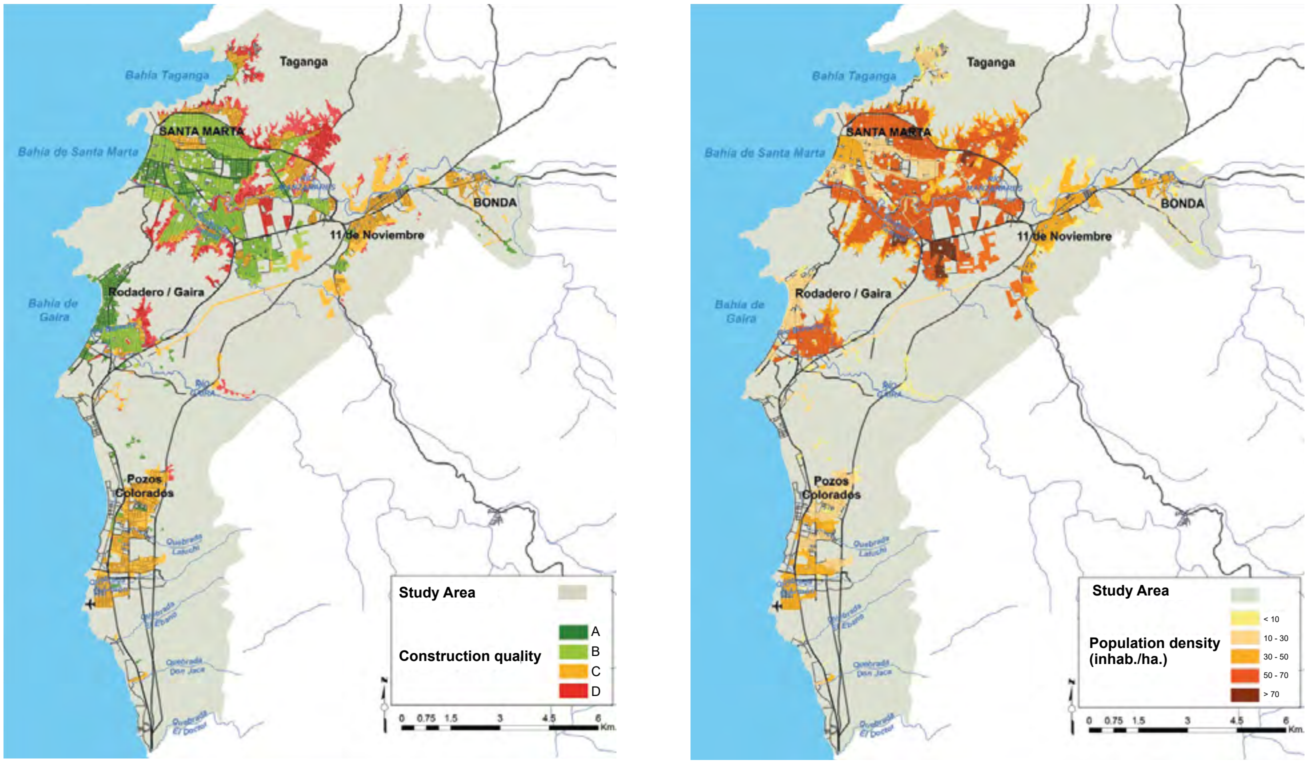


Figure 12 | Left) Example of the geographical distribution of buildings according to their construction quality. Right) Example of the population density map used in Santa Marta, Colombia.

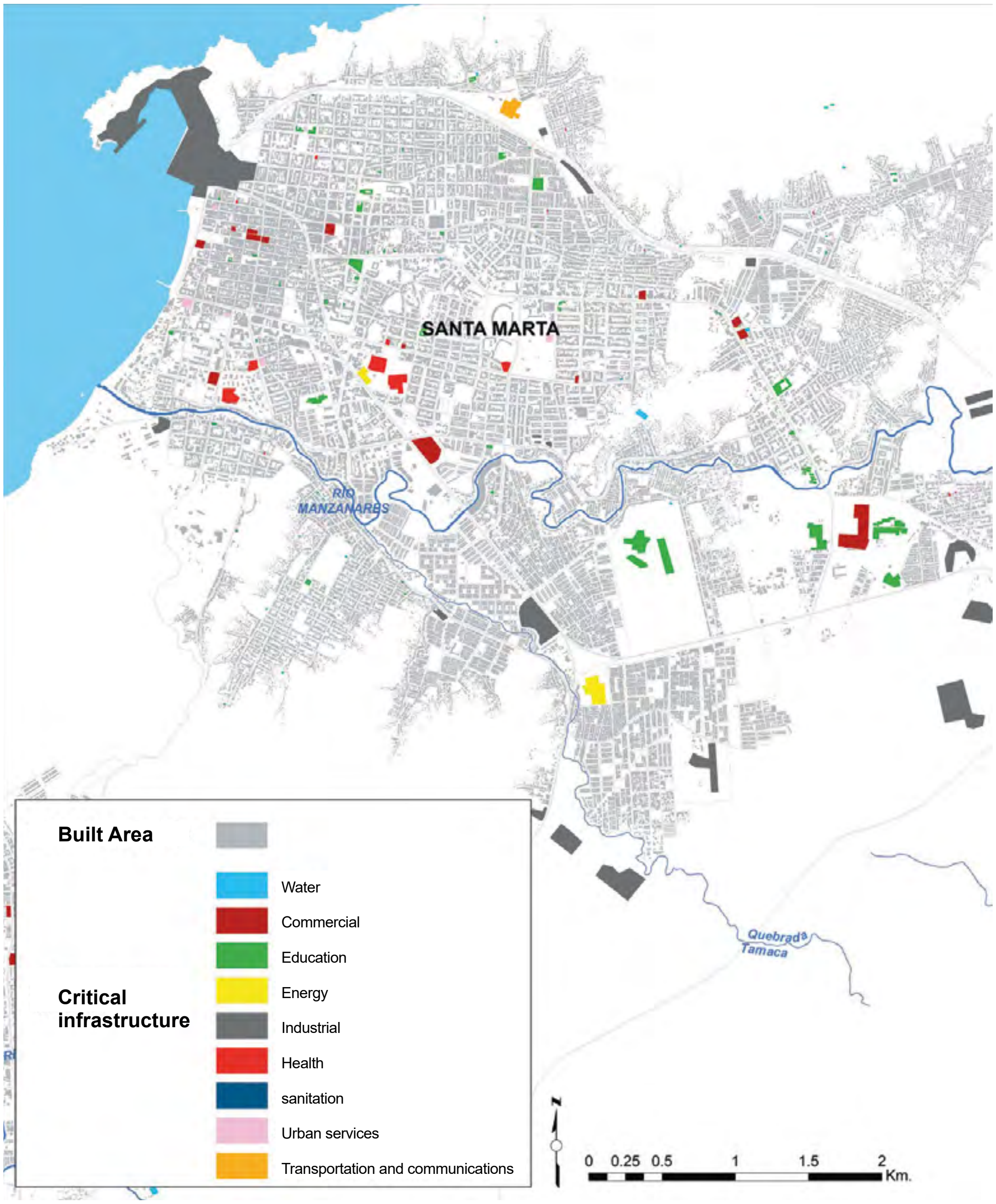


Figure 13 | Example of the geographical distribution of critical infrastructure, Santa Marta, Colombia.

2

Quantification of hazards —

2

This section will characterize the hazard associated with each of the risks considered in this document, except for the risk of urban drought which, due to being a slow-onset risk, entails certain peculiarities in the vulnerability and risk analysis and will therefore be analyzed separately in a specific section 4.

2.1 Riverine and pluvial flood hazard

The potential causes of flooding of inland cities and some coastal cities (those located in an area above sea level, like Lima and Trujillo in Peru – included in the ESCI) are local rainfall and/or the overflowing of rivers that run across them. In both cases, the dominant variable is the rainfall (local or remote) and the derived variables characterizing the hazard are mainly the water depth and velocity in the flooded areas.

In general, most cities in the world are located near a river of a certain importance that was originally (and sometimes even at present) used as a source of water supply and as a waste receiving medium. Such river was fed by other smaller streams and creeks that usually had intermittent flow which, as cities expended and consolidated, were perceived as mobility barriers and wasted spaces from an urban-use standpoint.

In the case of cities located in active alluvial lands (terraces below the potential flood elevation of a river), their location itself entails a certain level of risk from riverine flood – even without considering anthropic processes. Strictly speaking, this base risk can be considered natural because it is part of the sedimentation cycle and, besides, it brings benefits in the form of fertile soils that progressively fill in the valleys. However, the appearance and growth of cities usually implies the irruption of non-natural factors that worsen such base risk:

a. Urban growth modifies and often minimizes the riverine space, reducing it to an increasingly narrow corridor limited by dikes or walls in certain sections, with few expansion areas. Additionally, the construction of bridges often leads to a flow blockage, particularly during flood events.

b. Land use transformation processes at a regional level, which affect catchment areas, modify the hydrodynamic and morphological working conditions of the river. For instance, deforestation in catchment areas results in a temporary surplus of sedimentary load, higher variability of the water regime and, in many cases, increased flood flows.

In addition to these local and regional factors, there is the local climate change due to global warming.

If the fate of the main rivers in growing cities is to see their natural space reduced and their catchment areas modified, the fate of smaller streams and creeks is usually more dramatic: entire stretches are filled in, moved underground or, at best, reduced to a concrete section with reduced dimensions. Consequently, many cities – particularly in LAC – suffer relatively frequent floods due to the inability of their drainage networks to remove rainwater produced locally or coming from bordering slopes. These floods are usually called pluvial and have certain characteristic features that distinguish them from flooding caused by the overflow of large rivers:

- They occur regularly (sometimes more than once a year) and they are connected to short and intense events of local rainfall (usually lasting less than one hour)
- They generally cause few human losses and moderate material damage, at least directly, but they usually produce the halt or slowdown of commercial activities, the collapse of urban mobility and increased work absenteeism during several days a year.
- The affected people learn to live with this type of flooding, often by implementing simple and rudimentary adaptation mechanisms (elevation bases in dwellings, isolating gates in doors, elevated areas to protect furniture and electrical appliances, etc.).
- In the medium and long term, they hinder the development and improvement of urban spaces and produce a progressive devaluation and impoverishment of the affected areas.

The assessment of the riverine flooding hazard in a city comprises the following general steps:

1. **Selection of the river stretch(es) subject to study and delimitation of its(their) catchment areas.**

The river stretches to be considered are those located in areas that are subject to a potential riverine flooding risk and that also accommodate physical assets or human activities that can be affected by the flood. The length of the stretches to be studied should be measured with looseness, covering a certain distance upstream and downstream from the exact area of interest. For hydraulic reasons, it is convenient that the initial and final sections of the stretches under study be located in morphologically stable areas (if possible, in non-alluvial riverbeds with rocky geological substrate) and far from singular infrastructures such as bridges, diversion dams, etc. The delimitation of the catchment areas that feed their waters into the selected stretches (influence area) is based on a non-detailed topography of the land, and there are several programs that can be used to carry out this task. A detailed topography will be afterwards required to make hydraulic calculations.

2. **Physical characterization of catchment areas (see section 1.3.1).**

The type of information required to characterize the hydrological behavior of catchment areas depends on the availability of information in each country or region, as well as on the approach adopted for hydrologic modelling (see point 4 below). It is usually necessary to have knowledge on the land uses, and especially on the forest and cropping area, as well as some lithological and edaphological information to characterize the structure and behavior of soils.

3. **Characterization of climate, with especial consideration to the spatiotemporal characterization of extreme rainfall.**

This is one of the most important tasks in any riverine flood risk study and, depending on the amount and quality of the available instrument data, it may require different doses of expert judgement. The most common approach (framed within the pseudo-probabilistic techniques, following the IDB[1] language) is to define storms (also denominated hyetographs) with fixed duration, magnitude and time structure, for each return period. This way, the pseudo-probabilistic hazard assessment is reduced to a single-variable problem (univariate) and the derived variables (flows, levels and, finally, damage) directly inherit the probability associated with the dominant variable (in this case, the rainfall).

As regards the spatial distribution of rainfall, it is usual to introduce a areal reduction coefficient which, in a simple way and without looking into the background physical processes, reduces the total rainfall associated with a point and extends it to a non-homogenous area. This relatively simple approach is valid for small or mid-sized catchment areas (less than 10,000 km^2 as order of magnitude) that are relatively homogenous (without major bioclimatic gradients or geological variations). Among these methods, there is the Soil Conservation Service (SCS) curve number, which is widespread in LAC.

For bigger and more complex catchment areas, the determination of floods behavior generally requires more advanced studies, and it is not always feasible or justifiable to reduce it to one problem with one dominant weather variable, which transfers its probability of occurrence to the rest. In a catchment area of a certain extension, for instance, the total rainfall might be as relevant as the propagation of rainfall fronts or the synchronization of the rainfall registered in different valleys that connect their waters with a certain time lag. It should be noted that in these more complex cases, separating for operative purposes the characterization of rainfall from the hydrological assessment (see the following point) ceases to be valid, and the water flow at the beginning of the stretch under study would become the dominant variable, whose probability comes from the way in which the rainfall combines with its spatiotemporal variability, the land and the topology of the river network. Therefore, the pseudo-probabilistic approach would be applicable once the flow regime at the beginning of the stretch has been determined as a result of a fully-probabilistic analysis (according to IDB's terminology).

4. Implementation of hydrological models to transform rainfall events into river flows along the stretches under study.

In order to carry out the rainfall discharge transformation, there are many procedures (see Beven 2012), from the use of tables or empirical abacus, to models requiring a 3D discretization of the catchment area to model complete flow equations. In between, there are the conceptual models that can divide the land into sub-catchment areas (aggregate models) or into equal-sized cells (distributed models); the semi-distributed models use a hybrid approach (certain data on a cell scale is averaged on a larger hydrological unit scale). These conceptual models, in all of their forms, are generally suitable for making hydrology calculations in risk studies, and are usually well balanced in terms of the input data required, the number of parameters and the ease of use. Most conceptual models divide the runoff generation process into two sequential sub-processes: 1) calculation of abstractions and determination of the net rainfall; and 2) transit of the net rainfall to the calculation point. In conceptual models it is also usual for both sub-processes to be represented by a series of tanks, one being non-linear to calculate abstractions and at least two with linear behavior (or one non-linear) for routing (subsurface and underground flows follow a slow path, whereas surface flows have a fast response).

In cases where, in line with the considerations made in the preceding point, it is possible to separate the calculation of design storms from the hydrological analysis, the hydrology is usually addressed using an

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[1] The Disaster and Climate Change Methodology and Guide. IADB. Draft version. July 2019.

events-based approach, so that each design hyetograph (storm) is bi-univocally associated with a flow evolution curve (hydrograph). In this case, abstractions are usually calculated by using the curve number procedure, whereas transit is calculated by using the unit hydrograph method (Chow, 1964).

When more degrees of freedom are introduced into the system, and the dominant variable ceases to be the total rainfall associated with a storm with its univariate probability function, it makes sense to adopt a continuous hydrologic simulation approach, or at least one based on the simulation of a large number of events. Continuous hydrologic simulation models will be broadly described in section 4 regarding the urban drought risk.

5. Application of a hydraulic model that, based on the topography of the river channel and its adjacent areas, provides water levels and velocities.

The last step when assessing the riverine flood risk is the conversion of the flows obtained at the beginning of each stretch into water levels and velocities. It is at this point that the quality and resolution of the available topography becomes important, both inside and outside the river channel.

There are many hydraulic models capable of providing water levels and velocities in a calculation domain, based on different approximations to the Navier-Stokes equations governing the universal behavior of fluids. The models commonly used in river engineering usually adopt simplifications related to the vertical structure of the velocity and acceleration fields, therefore solving the 1 or 2 dimensional Saint-Venant equations (Cunge, Holly and Verwey, 1980). 1-D models are the simplest and are suitable when the flow has a dominant direction, which is the case of most rivers with narrow floodplains that are well connected to the main channel. During the last years, there has been an increase in the use of 2-D models to solve flow equations; although they are more demanding in computational terms, they do not assume a dominant flow direction and can, therefore, be used to simulate more complex patterns of water circulation, typically found in estuaries and large floodplains. Some models use a mixed approach: 1-D for the flow within the river channel itself and 2-D for the flow in adjacent areas. There exist many numerical hydraulic simulation packages, both free and under license, which differ in terms of their input and output interface, gridding tools, algorithms for the numerical solution of equations and supplementary features (introduction of bridges and other structures, transportation of sediments, etc.).

To calculate pluvial floods, the same steps described above must be followed, with the peculiarity that there is usually no need to apply a hydrologic model independent from the hydraulic model to the catchment areas, as these are usually formed by the urban area itself and the adjacent lands. Otherwise, except for step number four, which can be omitted, the risk studies on pluvial flooding follow the general methodology detailed before. However, some operative differences in comparison with riverine floods are worth mentioning:

- The quality of the input DTM is a more critical factor in the calculation of floods from rainfall than in other types of flood. Runoff generation and accumulation processes are very influenced by the presence of local elements such as walls, ditches and fillings related to roads and other linear works, which are not always included in the available topographic maps. Many of the global altimetry databases (see section 1.3.1) have an inadequate spatial resolution to analyze floods in dense urban areas, as they provide unreal pixel heights because they average the street level with that of the roof of the neighboring buildings.

- Design storms associated with pluvial flooding tend to be shorter than those generating riverine floods. Due to this fact, it is necessary to characterize rain gusts with a high temporal resolution (generally, 5 or 10 minutes), which requires data that it is not always available or that has been recorded for too short periods of time to define the extremes regime. Strictly speaking, pluvial floods are associated not so much with storms, but with downpours or singular gusts of rainfall within a storm. Moreover, the critical duration of rainfall gusts in a specific area may depend on the storage and drainage capacity of the existing drainage system, and not just on the geometry of the catchment area, so it must be calculated through a trial-and-error procedure (see the next point).

- The hydrology in urban or highly urbanized catchment areas has specific methods and tools that differ from the ones used in rural or scarcely built catchment areas. In the first place, the time of response depends not just on the geometry (generally characterized by a characteristic length and an average slope), but also on the proportion of the impervious area and on the structure of the existing drainage system. In addition, the use of the curve number method combined with the unit hydrograph might be inappropriate. Most of the hydraulic models available support different calculation approximations to predict the runoff generated by local rainfall.

- As already mentioned, local floods are very influenced by the existing urban drainage systems, both underground and in open air (trenches, ditches, median strips, etc.). Hydraulic models must incorporate the existing urban drainage systems (at least in simplified form) for risk results to be reliable.

Figure 14 | Illustrative map of maximum elevations and maximum velocities for a flooding event of T=100 years, in the prioritized area of Tegucigalpa, Honduras.

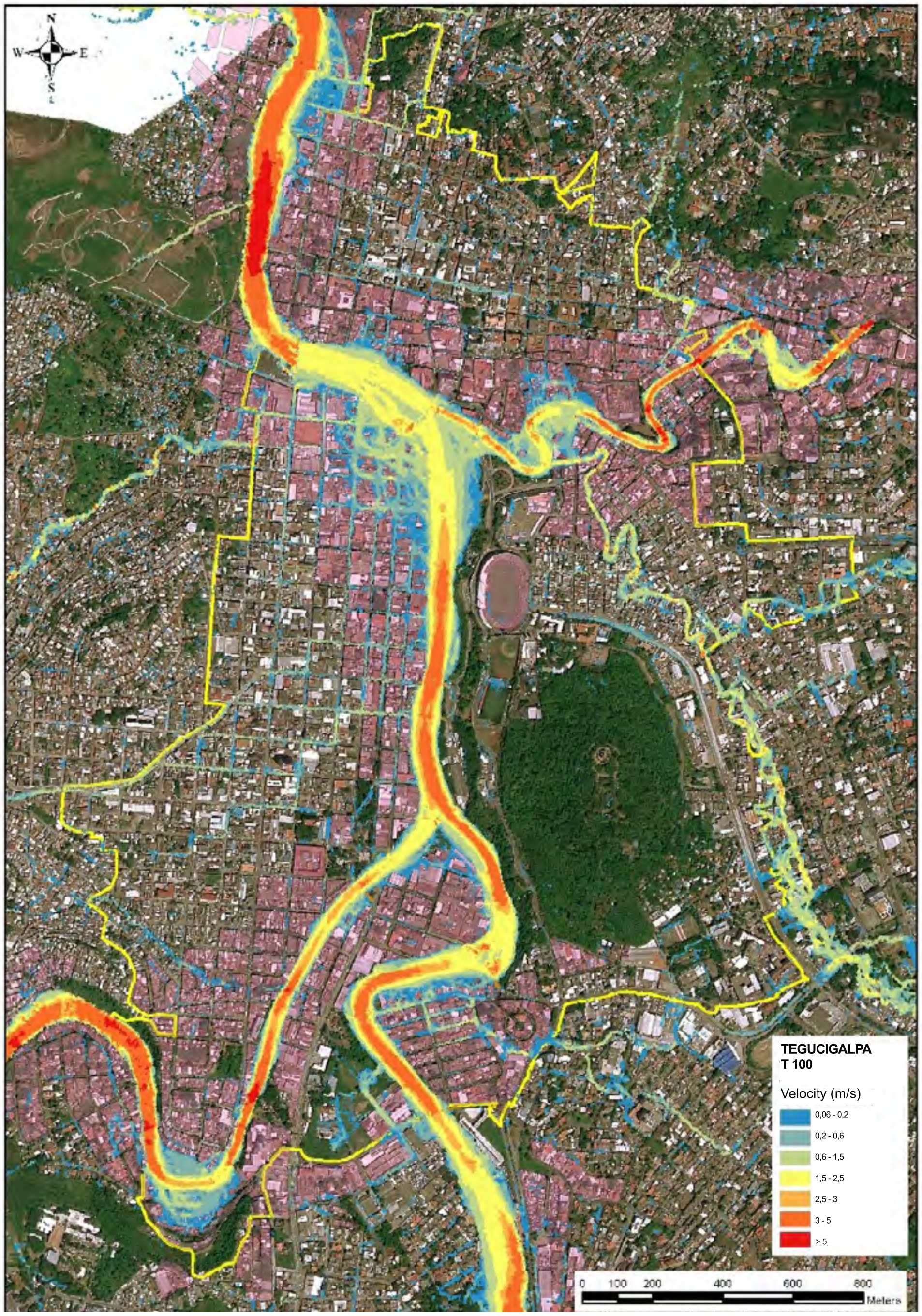

Figure 14 | Illustrative map of maximum elevations and maximum velocities for a flooding event of T=100 years, in the prioritized area of Tegucigalpa, Honduras.

2.2 Extreme wind hazard

Extreme wind events in tropical areas are mainly produced by tropical cyclones, as is the case of the cities of Belize (Belize), Campeche (Mexico), Bridgetown (Barbados) and Santiago de Los Caballeros (Dominican Republic), among others from the ESCI . While some of these cyclones are categorized as hurricanes, which produce devastating consequences, most of them are tropical storms with less damaging consequences, which should nevertheless be considered for an adequate statistical characterization of the extreme wind hazard. Additionally, it must be kept in mind that there are cities in LAC that can suffer significant economic and human damage although they are not in a hurricane-affected area, as is the case of the city of Panama. Therefore, there are two different methodologies to quantify this hazard: one for extreme winds produced by tropical cyclones, and another one for extreme winds with no direct relationship with this type of events. In both cases, the main variable to be quantified is the maximum wind speed 10 meters above sea level, for which different statistics techniques of selection, simulation, classification and numerical modelling can be used. This way, it is possible to statistically reproduce and characterize the spatial distribution and magnitude of this variable in order to quantify its value for different return periods.

Extreme winds associated with tropical cyclones

To calculate the tropical cyclone extreme wind hazard, it is recommended to use a fully-probabilistic method, due to the difficulty in identifying one single dominant source variable (there is no single hurricane with which a certain return period in terms of generated winds can be associated). Overall, the methodology comprises the following steps:

1. Selection of historic cyclones observed in the area of interest.

It is important to have an as complete as possible input database of tropical cyclones and select those whose track passed across the city under study or its influence area, producing significant winds. Usually, a circular area or coast segment around the city is delimited and all the cyclones whose track passes across that area are selected.

There are different databases characterizing historic cyclones, including hurricanes and tropical storms, such as the HURDAT database, which includes all the tropical storms and cyclones occurred in the North Atlantic from 1851 until today (Jarvinen, Neuman and Davis, 1988; Landsea et al., 2004), and NOAA's IBTrACS global database (Knapp et al., 2010), among others.

2. Generation of synthetic cyclones to supplement the set of observed cyclones.

The number of events included in a historical database that make landfall in a local area are very limited and are usually not enough for a statistical characterization of wind speed in an extreme regime. It is, therefore, necessary to increase the number of events, which is usually done through stochastic methods. The use of this type of mathematical simulation methods was implemented by (Russell, 1969, 1971) for the coast of Texas, and many other authors have been using them ever since (Batts, Simiu, and Russell 1980; Vickery and Twisdale 1995a, 1995b; Nakajo et al. 2014; etc.).

These methods are based on Montecarlo simulations, where a sequence of synthetic cyclones is obtained from the specific statistics (joint probability functions and time correlation) of each of the main parameters of the historical events, the most used being: wind intensity (pressure deficit), track, translation speed, minimum pressure at sea level, and cyclostrophic radius. By generating synthetic tracks, it is possible to generate tropical cyclones or hurricanes that have not been observed, but whose track and intensity are totally reasonable and compatible with the available observations.

3. Simulation of wind associated with cyclones (wind field model).

Once the tracks of all synthetic cyclones have been obtained, the next step is to obtain the wind field (speed and head) associated with each instant of the track of each cyclone.

Tropical cyclones are among the most difficult atmospheric phenomena to describe and predict, even with highly sophisticated models. Wind measurements (from surface platforms, satellites and reconnaissance aircrafts) may be available for a cyclone before and after it makes landfall, but they are rarely enough to describe the three-dimensional wind structures that are in constant change during the whole process.

In view of this, it is common practice to use different types of models, going from simple semi-empirical models, to parametric models (Holland, 1980; Bretschneider, 1990; Silva et al., 2003) and to more complex models that simulate the whole process, from the formation of a cyclone in the ocean until it dissipates. The latter models use the non-linear complete solution to the movement equations of a cyclone, and the intensity remains constant until the cyclone achieves landfall, after which it decays, using filling rate models (Peter J. Vickery et al. 2000a; P. J. Vickery, Skerlj, and Twisdale 2000b).

All of these models provide the wind field of a cyclone based on different variables, with the most common being cyclone intensity (pressure deficit), translation speed, sea surface temperature and cyclostrophic radius.

CALCULATION CONSIDERATIONS

The high computing costs associated with the simulation of all the synthetic cyclones obtained can be reduced by selecting a representative number of standard cyclones using data mining and classification techniques. The wind produced by cyclones that are not specifically simulated can be interpolated from simulated cyclones data, thus rebuilding the complete series.

4. Obtaining the extreme regime of wind speed.

The next step is to assess the extreme regime of winds based on the results obtained from all of the cyclones analyzed. The result is the maximum wind speed 10 meters above sea level for different return periods, obtained through statistical techniques. Note that it is common for the same cyclone to generate extreme winds with different directions as it moves and its route evolves across the territory.

5. Effect of ground roughness.

The interaction of the wind field and the terrain produces a spatial variation of the wind field, so the assessment of ground roughness is a critical component in wind modelling. As the surface becomes rougher the wind speed decreases near the ground, although it remains invariable at a higher level. As a result of this, the wind forces experienced by the structures located in a typical urban environment are lower than those experienced by buildings located in relatively unobstructed regions, such as coastal areas.

To account for the effect of ground roughness on the wind field, it is necessary to apply complex models that characterize its non-linear behavior. This type of models is not usually used – unless there are considerable topographic features that significantly modify the wind field – due to its high computing cost (e.g., an urban area with skyscrapers).

A simple approximation, usually adopted in building codes, is to apply a correction factor to the wind speed in open terrain, which depends on the category of exposure of the local terrain. This factor, denominated typical roughness length of the terrain, is a function of the height and dispersion of buildings, trees and other obstructions existing on the surface. In this regard, many studies have attempted to characterize ground roughness in the last decades, but researchers have not yet agreed upon a value for the different types of terrain, and there is thus a wide range of values (see Wieringa 1992; Wierngа 1993; Simiu and Scanlan 1996). In addition, there are also some simple analytic expressions (see Lettau 1969) that calculate this factor as a function of the height, the area of the obstacles, and the area of the terrain under study.

There are currently no databases with this type of information, so it is common practice to assign a typical roughness length value to each type of land use based on the available information on land use.

Extreme winds not associated with tropical cyclones

The procedure to calculate the extreme wind hazard not associated with tropical cyclones is much simpler; it only requires following the last two steps, which implies adopting a pseudo-probabilistic approach:

1. **Obtaining the extreme regime of wind speed.**

The wind speed and direction values (obtained from local weather stations) are used as input data to characterize the extreme regime, and thus obtain the maximum wind speeds for different return periods. If there are no weather stations in the area under study, or if the information is not sufficient, satellite data from existing databases can be used (see section 1.3.2).

2. **Effect of ground roughness.**

If the city has a complex orography, or if the ground roughness is expected to significantly affect the value of the wind speed, then the wind speed is modified at 10 m above sea level by applying the typical roughness length as a correction factor. Box 2 shows an example calculation of the wind hazard in Panama City.

The ultimate goal of the section on hazards is to obtain the probability of occurrence of the variable capable of producing damage in the physical space: for floods, maximum water depth and water velocity; for wind, peak speed at ground level; for coastal erosion, maximum shoreline retreat.

BOX 2 —

Assessment of the wind hazard in Panama city, Panama

Problem

In Panama city, extreme winds are currently the second most damaging hazard after floods. Damage caused by this hazard is common in city areas where dwellings are built with tile roofs and light envelopes, which are highly vulnerable to extreme winds.

Methodology

The orography of Panama city is complex for the quantification of the extreme wind hazard, so a computational fluid dynamics (CFD) numerical model has been used, as it enables studying the aerodynamic processes of wind in complex topography conditions. With this model, it is possible to obtain a spatial variation of the wind field resulting from its interaction with the orography, characterizing its non-linear behavior. The approach applied is the pseudo-probabilistic one based on calculation events, according to the terminology adopted by the IDB.

To apply the model, a three-dimensional numerical grid has been designed for northerly winds – which are the ones prevailing in the study area – which includes the most significant elements of the orography. The grid has been designed with varying cell sizes, with coarser cell sizes in the upper area and finer cell sizes in the lower area of the grid.

To represent profile transformations due to ground roughness, different roughness coefficients have been introduced according to the type of ground. With this spatial variation of the coefficient, the wind behavior values obtained are closer to reality.

As a boundary condition, the model also requires steady wind in a perpendicular direction to the calculation grid, in this case at an altitude of 1,000 meters, to incorporate the effect of the mountains located to the north of Panama city. Because the wind regime in that area at said altitude not known, the solution has been to introduce a wind that generates, in the most exposed areas of the grid (represented by the top 5% of cells with greater wind intensity) and at an altitude of 10 meters, the speeds obtained from meteorological stations for the different return periods.

Results

The results of the wind hazard calculation are the values of the average speed of stationary winds obtained for all of the three-dimensional grid points. Figure 15 shows the module of the speeds obtained and different maps for different heights, illustrating the effect of orography on the spatial field of wind.

The figure shows the shadow effect produced by the orography behind the mountains (patterns represented in blue), generating areas less exposed to the effect of the wind, as well as areas where the wind incidence is greater and speed values are higher (represented in red). It can also be observed how the effect of orography diminishes as the height increases; the figures showing planes that are more elevated from the ground show more spatially uniform wind fields than those located in areas that are close to the ground.

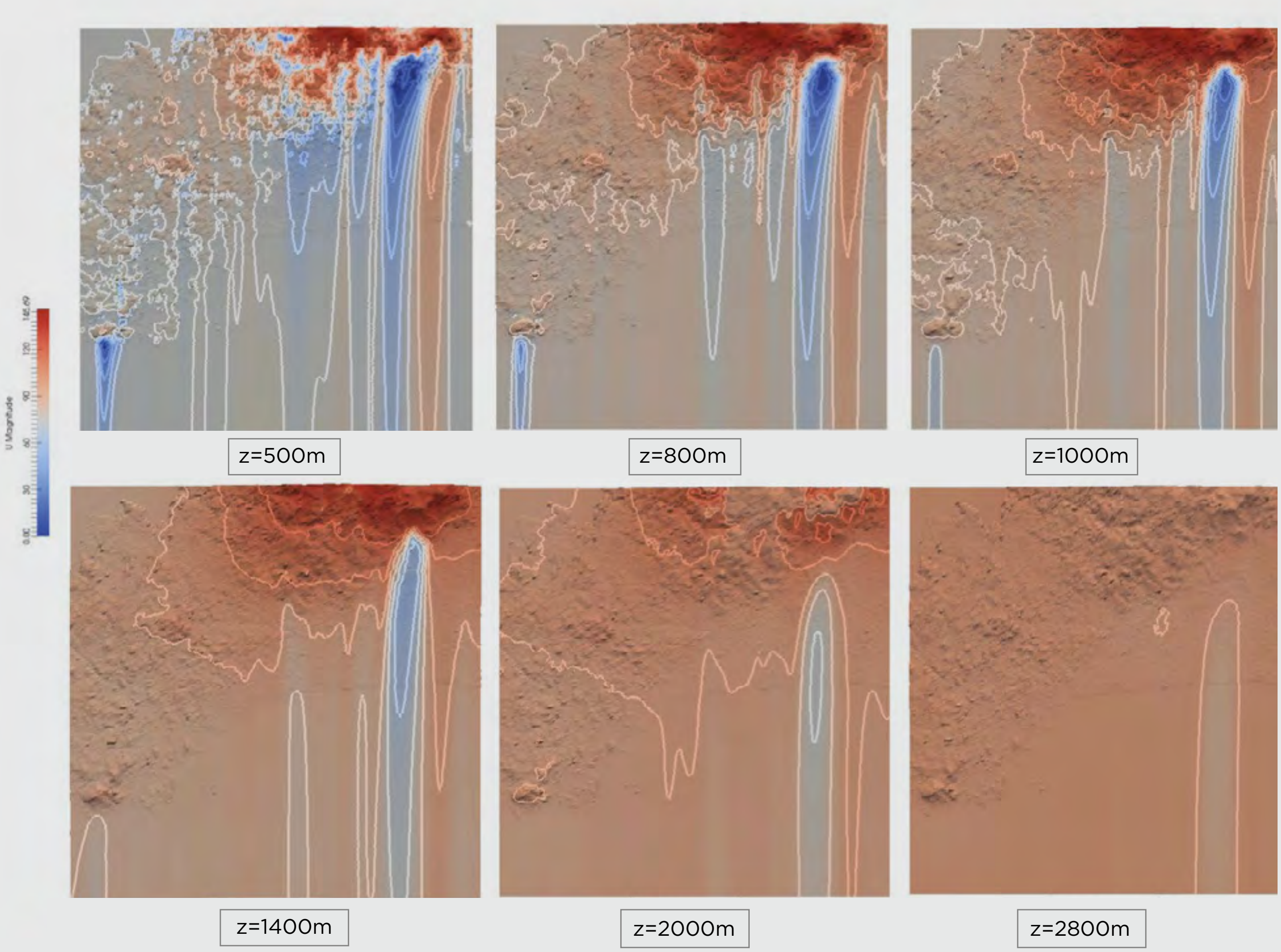

Figure 15 | Results of the wind fields at different heights for northerly wind blowing at 150 km/h in Panama City. The colors represent the value of the wind speed module.

2.3 Coastal flood hazard

Coastal floods are produced by a temporary sea level rise, potentially combined with waves, near the coastline. Despite their apparent simplicity, the physical phenomena produced in the sea-land interface are very complex and hard to predict. In the first place, the average sea level results from a combination of two types of independent phenomena: the astronomic tide, associated with the relative movement of the Earth, the moon and other planets, and the meteorological tide, defined as the sea level variation effect produced by the wind and local atmospheric pressure anomalies. As for the possible presence of waves, they not only entail an oscillating movement from the waves themselves, but may also lead to a slower oscillation of the water level generated by the propagation of wave trains – the so called long wave. On top of these overlapping processes, in the case of beaches or low gradient areas, the wave breaking also produces a momentary level rise (run-up) and a magnification of the said long wave, which in turn has a static component (set-up) and another almost periodic component (surf-beat). Ultimately, while the coastline is relatively well defined in cliff areas, rocky sections, or sections that have been hardened through seawalls, in low sandy stretches the coastline becomes a dynamic entity that is subject to morphological processes that transform the beach profile and the beach plan shape, as a result of the interaction between sediments and the acting dynamics, in a context of high energy dissipation (Dean and Dalrymple, 2004).

Considering this complex overlapping of processes, it is evident that a detailed modelling of all the physical phenomena that can be present in a coastal flood event is not viable for practical purposes, and it is therefore necessary to adopt some simplifications and working hypotheses. Again, as in the case of riverine floods, it is convenient to reduce the coastal flood phenomenon to a minimum number of dominant variables, from which the rest of secondary and derived variables can be obtained.

The next paragraphs summarize the general steps to assess the flood hazard in a stretch of coast by adopting a pseudo-probabilistic method, which could be converted into fully probabilistic if deemed convenient.

1. Analysis of the maritime climate in open sea and characterization of storm events.

In the first place, it is necessary to study the sea dynamics without the influence of coastal geographic features and local bathymetry. This implies characterizing the extreme wave regime in deep water through their directional spectrum or, for practical purposes, quantifying their three most relevant parameters: wave height (significant or root mean square), period (mean or peak), and peak direction (possibly coupled with some angular spreading parameter). It is also necessary to obtain the levels regime (which include the astronomic tide and atmospheric pressure variations; in open sea, sea level rise caused by the wind is insignificant). Based on these analyses, a number of representative storms will be selected and assigned a probability of occurrence.

2. Propagation of waves to the coastline.

The sea conditions characterized in deep water will change as the waves approach the coast as a result of refraction, diffraction, shoaling and breaking processes, among others. In order to propagate waves to the limits of the maritime area, where the land area begins, there are different numerical models that solve the relevant oscillatory flow equations based on bathymetry and boundary conditions. In many cases, the maximum wave height reaching a wall or promenade is limited by the depth near the structure, rather than the incident waves.

3. Determination of the hydraulic boundary conditions in the perimeter of the land calculation domain.

The water flow capable of inland flooding during a coastal storm depends on the interaction between the local hydrodynamics and the element defining the coastline (usually a beach, a cliff, or an artificial protective structure). In the simplest case of a structure of known and stable shape, such as the wall of a seafront promenade or a cliff, the overtopping discharge will be a more or less complex function of the sea level, the inland water level, the incidental waves and the geometry of the structure (especially, its crest height, the material it is made of, and its seaward slope). While the sea level remains clearly below the crest height of the boundary element, the dominant phenomenon will be the wave overtopping, which will be pulsating in nature; the moment the sea level exceeds the height of the structure, the flow conditions become those of a spillway, producing a more intense and continuous inflow. In certain cases, to simplify calculations, it is the latter mechanism of flood flow over spillway that is taken into account, with the flows associated with wave overtopping being disregarded. If this simplifying hypothesis is assumed, then the calculations of wave propagation outlined in the preceding point may also be omitted or minimized.

When the boundary element or some of the bordering elements have a variable geometry, as is the case of a beach, the flooding conditions need to consider the geometry caused by the acting dynamics, rather than the historical or average geometry. This can be done by using empirical or process-based models that predict the variations in the beach profile shape, including a potential berm and an emerged beach, as a consequence of the action of the sea dynamics. For beaches separated from the mainland by walls, a variation in the beach profile shape entails changes in the depth at the foot of the wall, which in turn modifies the characteristics of the waves that produce a potential overtopping.

It should be noted that flow conditions should be assessed by coastline stretch, after conducting the most detailed possible characterization of the typology of the elements forming the land-sea edge. Only one vulnerable stretch, or a stretch where a collapse of the defense structure may possibly occur, may be enough to cause the flooding of an area of a city that is well protected in the rest of its perimeter.

4. Implementation of a hydraulic model to determine flow levels and velocities.

Here, many of the considerations in point 5 of the methodology to calculate the riverine and pluvial flooding hazard are valid. Coastal flood requires the application of a 2D hydraulic model with the same equations as for riverine flood and with a good base topography; the main difference is the nature of the boundary conditions, which, in the case of the coast, derive from the preceding methodological steps.

2.4 Quantification of coastal erosion processes

Coastal erosion is the process by which a stretch of coast experiences a progressive retreat of the coastline over time. Specific and seasonal variations in the shape of the plan and profile of a beach, with no long-term net gain or loss of material, may be of interest in the study of coastal flood risks, but are not considered as erosion hazard in this context. Although erosion can exist in different types of coast, this document will focus on the beaches as the physiographic units most commonly affected by this phenomenon. In order to understand and quantify the coastal erosion processes, it is necessary to estimate the sediment budget in the different stretches or sectors of the area under study over time, and to project such balance to characterize future situations. The main steps to carry out a study of the coastal erosion hazard are detailed below.

1. Delimitation of the area under study and separation into sectors and stretches

In studies on coastal erosion it is usually convenient to analyze not only the stretch of strict study (generally, the urban coastline), but also other adjacent coastline units which together form a physiographic unit. As a general rule, once the working area is defined, it is convenient to identify coast sectors, and inside them, stretches of study. The sectors are usually long beaches or groups of beaches with a similar orientation or configuration (km scale), whereas the stretches provide a narrower subdivision, usually of hundreds of meters. The subdivision in sectors and stretches is relatively arbitrary, but it is convenient that their separation limits be associated with geographic factors (capes, mouths of rivers, changes in the orientation or type of coast, etc.), or artificial elements (ports, breakwaters, filling areas, seafront promenades, etc.).

2. Information gathering and analysis of the historical evolution

As in the case of coastal flood, it is necessary to characterize waves in deep water, as well as the sea level regimes (see section 2.3.1). At the same time, it is necessary to have the most recent possible bathymetry, with enough resolution near the coast. In erosion hazard studies, it is particularly useful to have historical bathymetry, as well as pictures (aerial and rectified if possible, although oblique pictures showing the condition of the beach are also useful - in any case, specifying the date when taken), old nautical charts, historical city plans, drawings, etc. In general, it is necessary to gather any type of information that may help rebuild the historical evolution of the coast. It is also convenient to gather information on the date of construction and characteristics (standard sections, materials, geotechnical aspects) of maritime works built within the studied area, especially ports, reservoirs in river basins, dredging works, fillings, breakwaters, seaside promenades, etc.

3. Characterization of waves propagated in the study area and estimation of longshore transport

This task is closely related to the one included in section 2.3.2 for coastal flood hazard, although in this case it is necessary to characterize not only big storms, but also the average wave conditions. Additionally, whereas for coastal flood the focus is placed on obtaining the waves in the coastline, in erosion studies it is useful to have an estimation of the longitudinal currents derived from the propagation of waves, and the associated sediment transport. Most of the numerical wave propagation packages deliver this type of results.

4. Characterization of other sediment flows

Besides longshore transport, a coastal sector may be exposed to the following sediment input or loss processes:

- River inputs from their bed load and suspended load derived from watershed wash.
- Cliff inputs from wave erosion.
- Other flows (inputs or losses) between the littoral and the adjacent land areas, for example, due to wind transport.
- Losses due to sediments transported to deep littoral zones, outside the active beach profile.
- Flows originated by humans: beach filling, dredging works, sediment extraction from estuaries and river channels associated with the system, etc.

Of all these flows, the most common are river inputs and fillings or dredging originated by humans, although in each specific case it is necessary to investigate the importance of other processes. Whenever possible, flows should be characterized not only by their mean value, but also by their complete time series, with the available time discretization.

5. Sediment budget by stretch and determination of potential erosion rates

The sediment budget would be a simple subtraction of sediment inputs and outputs in each stretch under study, as obtained in the previous steps, but for the fact that each stretch depends on what happens in the adjacent stretches (except in enclosed beaches that are considered independent units for practical purposes), and, thus, their behavior and way of interaction are determined by the wave sequence considered. Therefore, strictly speaking, it would be necessary to introduce all flows in a numerical environment capable of modelling the system's global behavior by stretch, taking into account the time scale of the processes, their correlations and local morphological restrictions (e.g., the maximum width of the beach as a result of the local topography or the length of the supporting breakwaters).

In many cases, this is not a viable approach and it is enough to adopt a simplified approach involving establishing what has been and will be the net variation in the sediment budget in a coastal sector, in relation to certain equilibrium operating conditions that normally relate to a historical situation without maritime works (ports and breakwaters) and without alterations in river inputs. This provides a potential average deficit of sand, by stretch or as a whole, expressed as a flow (tons or m^3 of sand per year). It should be noted that, with this simplified approach, the deficit is denominated potential, since it is not affected by restrictions in the erodible sand volume, or by the presence of rigid elements such as seafront promenades and defense works; besides, it is a mean value that does not represent extreme situations associated with a specific event and, therefore, does not work to estimate the maximum advance of the sea during a storm.

The last step involves transforming the deficit, expressed as a volume flow (m^3/year), in a potential coastline recession rate (m/year), which is the most typical indicator of the coastal erosion hazard. For such purpose, the active profile must be moved inland until the volume between its starting and final positions, in a 1 meter-wide slice of beach, equals the calculated volume deficit. Under certain hypotheses, the coastline recession (x, in m per year) can be expressed as follows:

$$X = \frac{V}{h^* + B}$$

where V is the volume deficit (m^2/year), h*(m) is the depth of closure of the profile, and B (m) the height of the beach berm (see Calculation considerations).

The potential coastline recession rate associated with modifications in the sediment budget should not be confused with the potential recession associated with a sea level rise, as considered under climate change scenarios. Although these processes may appear in a similar way and have equivalent results, they derive from different causes, require different risk reduction approaches and may coexist independently.

In order to calculate coastline recession due to the sea level rise, the most direct method is the application of the so-called Bruun Rule, which, following simple geometric considerations, concludes that, notwithstanding the beach profile, the average recession of the coastline (x), associated with a sea level rise S (m), can be

$$x = S \cdot \frac{w}{h^* + B}$$

calculated as follows:

where W (m) is the length of the active profile, h*(m) is the depth of closure of the profile, and B (m) the

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The depth of closure or active depth h* of a beach profile is approximately 1.6 times the significant wave height exceeded for 12 hours a year (H_s12). The length of the active profile W depends, mainly, on the average size of the sand that makes it up and on the depth of closure: $W= (h^*/A)^{3/2}$ where A is roughly the average size of the sand (D_{50}) in mm; it may vary from tens of meters in low-energy reflecting beaches to many hundreds in dissipative beaches with intense waves. The height of the berm B depends on the local conditions of each beach. In case there is no data, a value of approximately 1-1.5 m may be adopted.

In order to determine the total recession rate of a beach sector under erosion and climate change conditions, the average erosion rate must be added to the equivalent recession rate associated with sea level rise (total expected recession divided by the number of years). Box 3 shows how these expressions were applied in the case of Cumana city in Venezuela.

In general, any city subject to a certain level of risk will require a program of measures combining infrastructure and management interventions like awareness-raising, training, land planning, reforms of the legal and institutional framework, etc. When designing risk reduction works it is important – whenever possible – to prioritize measures inspired by the natural operation of the territory where the intervention is made.

BOX 3

Assessment of the coastal erosion hazard in Cumana (Venezuela)

Problem

Coastal erosion in the metropolitan area of the city of Cumana is one of the natural hazards that most directly affects the sustainable future of the city, mainly due to the variability of the marine dynamics and the increase in the average sea level due to climate change.

Demographic growth and urban densification have led to a disorderly development in the coastline, sometimes leaving no standby or buffer areas in the coast, which exposes the dwellings and buildings to the action of the sea, increasing their vulnerability. Additionally, in 1972 a bypass channel was constructed in the Manzanares river (main river running through the city) in order to protect the city from riverine flood events. However, this deviation caused an undesired effect: a reduction in sand input from the river to the sea (silting along its last 8 km and sedimentation in the area adjacent to the river mouth), and consequently, the erosion of San Luis beach.

Methodology

The assessment of coastal erosion hazard in the city of Cumana has involved addressing two impacts:

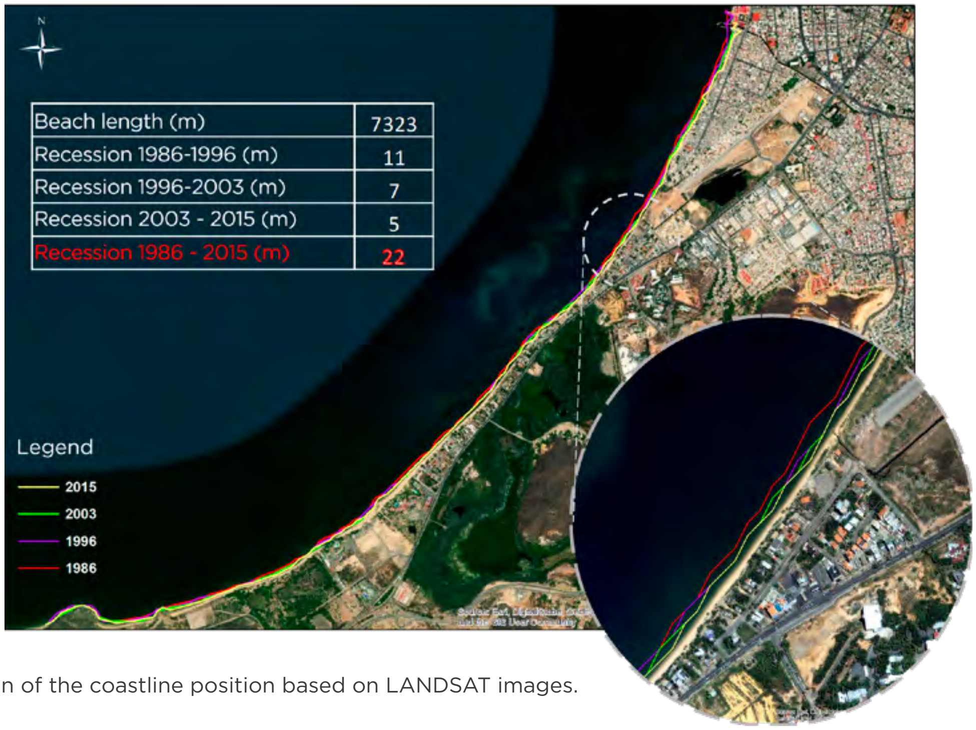
- Anthropic erosion: In order to calculate anthropic erosion, it is necessary to determine the marine dynamics at the foot of the beach. Thus, the wave sources arriving at San Luis beach have been identified, and by assessing points of interest on the coast and profiles perpendicular to it, the annual average transport caused by marine dynamics has been estimated. This transport calculation has been validated with the recession of the coastline position obtained from LANDSAT satellite images for different periods of time (Figure 16). The longshore transport of sediments caused by waves coming from the outer sea has been analyzed separately from the transport caused by waves from the Cariaco Gulf, and then the results have been included in the calculation to determine the average annual transport in San Luis beach.
- Erosion due to sea level rise caused by climate change: A calculation has been made of the beach recession due to sea level rise caused by climate change. The Bruun Rule has been applied to quantify the response of the beaches to the average sea level rise produced by climate change. To determine the trend in the average sea level variation due to climate change, sea level rise values for RCP 4.5 and 8.5 scenarios and for the 2030 and 2050 horizons have been obtained from IPCC estimations published in its last report (2013) and Slangen et al. 2014.

The final coastline has been defined as a linear overlapping of the two impacts in the coast area. Finally, according to the studies developed, lines of action are proposed to address both impacts sustainably.

Results

As regards anthropic erosion, results show that, on average, 8,000m^3/year of sand are being lost on the beach. Assuming that no actions are taken at San Luis beach, an average recession of the coastline position is estimated based on the average annual transport calculated, and applying this average recession to the 2030 and 2050 horizons, results are 9.4m and 22.0m of recession relative to the position in 2015.

Figure 17 shows the total recession as the addition of the recession induced by the average sea level rise due to climate change and the recession produced by longshore sediment transport assuming no actions are taken to control it (transport due to anthropic impact).



Beach length (m)	7323
Recession 1986-1996 (m)	11
Recession 1996-2003 (m)	7
Recession 2003 - 2015 (m)	5
Recession 1986 - 2015 (m)	22

Figure 16 | Evolution of the coastline position based on LANDSAT images.

Year	Scenario	Sea level rise (m)	Recession - Bruun Rule (m)	Total recession (m)
2030	RCP 4.5	0,13	2,88	12,30
	RCP 8.5	0,18	3,99	13,41
2050	RCP 4.5	0,24	5,32	27,29
	RCP 8.5	0,33	7,31	29,28

Figure 17 | Total recession of the coastline position in the study area, for 2030 and 2050, under RCP 4.5 and RCP 8.5.

2.5 Hurricane hazard

The passing of a hurricane through a city may involve a combination of all the above-mentioned hazards: flood (of the three considered types, i.e., riverine, urban and coastal), extreme winds and coastal erosion. Therefore, the characterization of the hurricane hazard should take into account the probability of occurrence of these events, including their evolution in time considering that, in general, the most critical instants of each particular phenomenon may not occur simultaneously.

Due to the complexity of the problem, the calculation procedures for this hazard usually adopt a number of simplifying hypotheses that may vary according to the case under study. As a more holistic approach, hurricane trace evolution models can be calibrated (see section 2.2) and used to generate wind, rainfall, and sea level fields through numerical simulation on a regional scale. The derived wind fields, apart from being a hazard themselves, may be used as input data in models to generate levels and waves that can be propagated to the area under study. Likewise, regional rainfall fields may be used to obtain the maximum flows in big catchment areas, which can be used to calculate the riverine flooding hazard. This is an arduous approach that requires plenty of data and numerous internal hypotheses in the different models used, which may lead to incoherent results, especially if a calibration is not performed.

A somewhat simpler approach is to select certain dominant climate variables (usually, wind and sea level rise in coastal cities, and wind with local rainfall in inland cities) and adjust a joint distribution function of extreme events using multivariate distributions (like copulas) or any other statistical procedure. As a result of this, different families of values are obtained for the dominant variables that have an equal probability, all of which characterize the hazard for a certain probability of occurrence.

In order to simplify the calculation even more (adopting a pseudo-probabilistic approach), time correlation patterns of the relevant phenomena may be assumed beforehand and used as a basis to obtain sets of values that characterize design events, entering directly into the univariate extreme regimes of the representative variables. Thus, the hazard associated with a 100-year hurricane in a certain city may be characterized through a set of combined events of rain, wind, river flow and sea level that are considered equiprobable. This procedure requires expert judgement and historical data when selecting the calculation events and the probabilities of the secondary variables associated with the main variable of each event that ultimately reflects the internal correlation of the physical phenomena involved.

When a city is exposed to flooding from a big river, the passing of a hurricane may produce extreme river flows as a result of the heavy rainfall, but such extreme river flows are normally desynchronized from the instant of the highest wind and local rainfall (as is the case of the big floods caused by the Choluteca river in Tegucigalpa, or the Belize river in the city of Belize). If such is the case, then it is recommended addressing this phenomenon with the methodology described for river flood hazard. Additionally, hurricanes may cause different degrees of damage to critical infrastructures that support some essential urban services such as water supply, sanitation, and power grids. These effects are very important in post-disaster management and will be discussed in section 3.4.

2.6 The effect of climate change in the calculation of hazards

The forecasts from the different general circulation models (GCMs) are used to characterize the average and extreme climate variability for a given horizon and emissions scenario and, therefore, to obtain the future regime, as well as representative time series of the most important hydroclimatic variables, including temperatures and rainfall. Data on extreme events, however, are scarcer, carry more errors from the use of measuring instruments (which affects calibration and validation), and are usually associated with physical processes that are more difficult to reproduce and with high space variability. Thus, generally speaking, climate models are not particularly suitable for projecting the extreme variations of the variables involved, especially those showing more time-space variability – like rain -, which will be addressed in the following recommendations.

Most of the climate models work with a horizontal spatial resolution that goes from tens to hundreds of kilometers, so many cities do not even represent a complete cell. Besides, many LAC cities are located at the foot of a mountain or in coastal features that cause local climate phenomena that are not contemplated in the models or are contemplated in a simplified fashion. Some countries and agencies have developed mesoscale models that are more adequate at first glance, but the orographic and convective effects are nevertheless difficult to reproduce. Whenever there is a need to apply climate model results to a specific city, it is convenient to validate that the historical series obtained from such model (which is called “data reanalysis”) are consistent with the available local historical records, and if they are not, then a method to adapt them must be applied.

The models’ resolution problem is not only spatial, but also temporal. In many cases, the analysis of pluvial flood or riverine flood hazard in small urban basins requires rainfall data on a 10-minute scale, or on an hourly scale at the most. In many cities, there are pluviometers or weather stations that provide this type of data which are used to build the expressions that provide information on how much rain can fall on a given period, for an extreme situation with a certain recurrence period, which are called intensity-duration-frequency (IDF) curves.

In studies of city risks, there is a need to estimate IDF curves for different future climate scenarios. To do this, the current IDF curves obtained from instrument records of sufficient duration are used as a starting point, and then some of the available projection methods are applied. This document will focus on discussing some statistical methods to carry out this task, which are often appropriate for this type of studies. However, provided that the necessary resources are available, dynamic methods based on the application of regional climate models can also be used. In practice, the problem of characterizing future extreme rainfall in a city, should start with a valid description of the present climate, so that its expected evolution patterns may afterwards be analyzed.

1. Determination of IDF curves for the current climate

The procedure to carry out this task, when enough instrument data with the adequate time resolution is available for the area under study, is described in specialized manuals (Chow, 1964). However, in many LAC cities, long series of rainfall data are only available on a daily scale, which impedes the direct calculation of IDF curves. An indirect method is to adopt curves from another place where this type of information is available and which can be considered similar to the studied area for climate purposes, due to either its geographic proximity or certain climate patterns. For extreme rainfall in a Caribbean city where the extreme climate is dominated by tropical storms, IDF curves from a place in the USA with a similar historical rate of hurricane occurrence (possibly weighted by its magnitude) may be used. Another alternative approach, which can be also used to supplement the previous one, is to use the TRMM (Tropical Rainfall Measurement Mission) database, which provides historical data from remote active and passive sensors every three hours in a 0.25° grid, calibrating it with local pluviometers. To calibrate the original TRMM data based on daily instrument data, regression models adjusted by month can be used (see the example of Belize City in Box 4). Once the calibrated series are obtained, they can be used as approximations to an instrument record with a three-hourly resolution to obtain IDF curves for a longer duration. The TRMM project, currently transformed into a more ambitious project denominated Global Precipitation Measurement (GPM), provides data recorded since 1997, which at present represents 20 years of available data. Thus, it is not advisable to use these series, even if calibrated, to calculate rainfall associated with a return period exceeding 5 or 10 years. For rainfall with less than a three-hour duration, the options are to use the analogues method, or otherwise adjust analytical expressions to the available points and extrapolate them to shorter durations.

2. Analysis of the effect of climate change on current IDF curves.

The analysis of the riverine and pluvial flooding hazard under climate change in cities requires the characterization of the IDF curves associated with future rainfall. To do this, there are different methods, which are more or less intensive in terms of data and resources. The most basic approach, which is often inappropriate, is to multiply the current curves by a series of factors (potentially different for each return period, RCP and time horizon) resulting from the analysis of the change between the extreme regime of current daily rainfall and the regime resulting from GCM projections. If the result is a reduction, the IDF curves for the current situation are usually kept, applying the precautionary principle.

An improvement to this procedure is to determine the change factors on a monthly scale, and then use them to evaluate the effect on IDF curves. If possible, it is advisable to move from these linear factors to more complex regression models, possibly by including covariates with predictors on a synoptic scale that are relevant for purposes of the relevant phenomenon (for instance, in the Caribbean, the sea surface temperature is a good predictor of the generation of tropical storms, which explain the occurrence of extreme rainfall). If a classification of the weather types is also made and representative climate patterns are determined on a regional scale, it is possible to determine a change in the occurrence ratio and transition probability in different climate change scenarios, and adjust them to a local scale, in terms of the relevant variable. As a practical example of the latter procedure, there is a study conducted for the city of Tegucigalpa (Honduras) under the ESCI (Box 5). It should be noted that these techniques can only be used to determine the behavior of future IDF curves for durations that are equal to or longer than the time resolution of the models upon which they are based. To extrapolate this information to rainfall of a shorter duration, either the shapes of the current climate curves are maintained, or regional climate models with a higher resolution are used (see, for example, Switzman et al. 2017).

CALCULATION CONSIDERATIONS

IDF curves are usually presented as derivable (soft) and monotonic-decreasing expressions that generally show a good adjustment through hyperbolic functions or other similar functions. Although this type of adjustment might be valid to make interpolations of available data, its validity must be confirmed when extrapolating and, especially, when predicting the behavior of short gusts of rainfall (less than 2-3 hours) where the trend might change. The extrapolation of the lower branch of the IDF curves from its middle stretch has to be carefully made, since in the lower time-scales, the baseline physical processes might be different.

These methods and others (see Fowler, Blenkinsop, and Tebaldi 2007 for a general classification of methods, and Gutmann et al. 2014 for a comparison of the performance of some of them in the USA) are included in the category of statistical downscaling techniques. It is also possible to apply climate simulation models to a regional or even local scale (sometimes coupled with ocean models) taking GCM results as boundary conditions, which is called dynamical downscaling. Dynamical techniques require more technical and computational resources than those based on statistical procedures and theoretically offer some advantages that do not always result in greater reliability of the results (see Wilby et al. 2009 for a general overview of the criteria that should be adopted to select a method, according to the type of adaptation under consideration).

In any case, the future projection of the hydrological effects of climate change is a task involving great uncertainty associated with multiple sources (Clark et al., 2016), some of which include extensive errors, so the measures derived from these analyses should be adaptable to a wide range of possible evolution scenarios, and should be based on the precautionary principle.

BOX 4 —

Characterization of short-duration extreme rainfall in Belize city under climate change

Problem

Belize City is exposed to frequent floods produced by a combination of local rainfall, riverine flooding and sea level rise. Although to protect the city from riverine flooding and sea level rise it is necessary to build defensive works in the perimeter of the city, the effect of local rainfall can be reduced through urban drainage works. To design sewer networks and pumping systems it is necessary to know the behavior of local rainfall in relatively short periods of time, in this case between one and three hours. In Belize City, there are five pluviometers that provide historical rainfall data on a daily scale, but the internal structure of storms is unknown, since there is no data with a lower time resolution. This lack of knowledge is transferred, with greater uncertainty, to future rainfall under climate change.

Methodology

To estimate the effects of climate change on extreme rainfall in Belize City, the first step was to determine the intensity-duration-frequency curves (IDF) for the current climate. The data used to do this was sourced from the TRMM 3B42 database of the Tropical Rainfall Measuring Mission Project (Figure 18), and was calibrated according to data from the St. John's College's pluviometer, which has a longer series. The TRMM data has a time resolution of 3 hours, but relates to a global grid with 0,25° cells (approximately 26 km) – hence the importance of local calibration.

It was found that, by introducing monthly correcting factors, the daily rainfall taken from the TRMM Project properly reproduces the precipitation climate in Belize City. Based on this statistical downscaling and the analysis of extremes of the 24-hour rainfall taken from the pluviometer (GEV adjustment with confidence bands), IDF curves were obtained for three-hour or longer durations. In order to obtain the lower tail of the curves (1 and 2-hour durations), polynomial adjustments of the available points were extrapolated, assuming a similar behavior to the IDF curves provided by NOAA for the city of Miami (Miami Beach Station, ID: 08-5658), considered analogous to Belize City in terms of extreme rainfall.

To project these current IDF curves into the future under climate change, the global NEX-GDDP (Earth Exchange Global Daily Downscaled Projections) database was used. This database contains many climate scenarios on a reduced scale, provided by 21 general circulation models. In this case, RCP 4.5 and 8.5 were selected. Once again, the model outputs for a control period (1986-2005) were adjusted to local conditions through monthly change factors to ensure that they accurately represent the local climate.

Results

The current IDF curves obtained for Belize City are shown in Figure 18, while yearly average change factors for different time horizons and two RCPs are shown in Table 5. It can be observed that the change factor results show greater dispersion and are less consistent as their return period increases, largely due to discrepancies among the general circulation models used and their limitation to reproduce extreme events, many of which are related to the origin and evolution of tropical storms in the region. As a practical approach, it was decided to adopt the resulting coefficients for the 10-year period and RCP 8.5, averaging the intermediate horizon (2046-2065) and the long-term horizon (2081-2100). The result is an estimated increase of 10.3% in extreme rainfall in Belize City under climate change.

In addition, due to the associated uncertainty, the results were validated with the forecasts based on dynamic methods (regional climate models) made by Knutson et al. 2013, which provide estimates of an increase in rainfall associated with hurricanes of the same magnitude (9-12%) in areas located more than 100km away from the center of the hurricane.

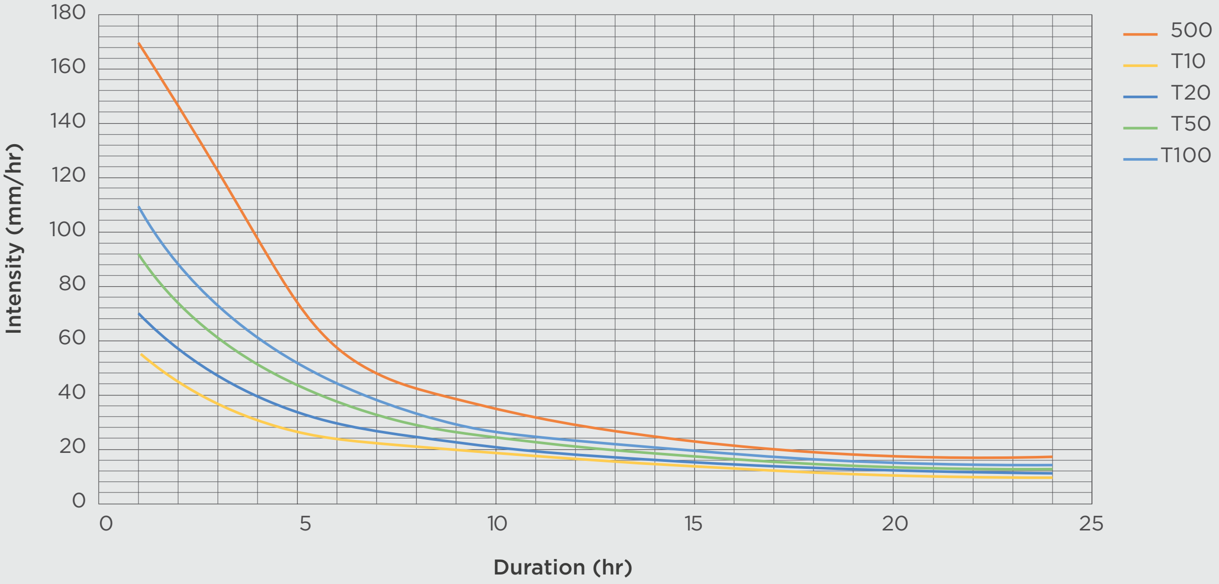


Figure 18 | IDF curves obtained for Belize City in its current situation.

		T (YEARS)					
	PERIOD	5	10	20	50	100	500
RCP 4.5	2016-2035	0.997	0.993	0.988	0.980	0.972	0.932
	2046-2065	1.022	0.999	0.971	0.923	0.877	0.715
	2081-2100	1.040	1.026	1.008	0.976	0.943	0.821
RCP 8.5	2016-2035	1.160	1.138	1.108	1.055	1.003	0.822
	2046-2065	1.145	1.162	1.184	1.221	1.258	1.374
	2081-2100	1.066	1.043	1.013	0.965	0.921	0.774

Table 5 | Change factors in Belize City for different horizons, emission scenarios and return periods, obtained from the adjustment of the NEX-GDDP database to local conditions.

BOX 5 —

Classification of weather types and analysis of the effect of climate change in Tegucigalpa (Honduras)

Problem

Tegucigalpa is located at the headwaters of the Choluteca basin. In 2017, there was a deficit of water for urban supply of about 45 million m^3 per year, which equals to an average unsatisfied demand of 100 liters per person per day, for a population of 1.2 million inhabitants. These figures are likely to increase significantly over the next decades, because of either population growth or lower rainfall – not to mention the progressive deterioration of the quality of the resource. It is important to establish as precisely as possible the potential effect of climate change on the rainfall regime in the basins supplying the city in order to set more appropriate and realistic development strategies, which include the feasibility of new regulation infrastructures. On top of this, the city still holds the tragic memory of hurricane Mitch, occurred in 1998, and knows that an excess of rainfall in a short period paradoxically implies another great hazard to the city.

Methodology

As part of the ESCI study, in order to assess the potential effect of climate change on the rainfall regime in the city's influence area, the types of climate in the region were classified according to the average sea surface temperature (SST), which is one of the variables that best explain the generation of tropical cyclones. When relating the SST with a zero to one index (SSTI), which indicates when the cyclonic activity (or the probability that a cyclone is formed) is higher, the identified weather-pattern sequence can be converted into a random series of tropical storms that can be numerically generated, in order to have enough data to characterize the regime of any associated variable (pressure, wind, waves, rainfall, etc.). In the case of rainfall, the R-Clipper model (Tuleya, DeMaria and Kuligowski, 2007) has been the tool used to obtain the rainfall field associated with the passing of a tropical cyclone.

Once the most characteristic weather types, their associated probability and the rules of transition from one to another have been selected, it is possible to apply the same type of analysis to the weather sequences generated by the different general circulation models under climate change for the next decades, and to analyze the variation in the probability of occurrence of each synoptic pattern according to the calculation period and the different RCPs. Such variation in the probabilities of the different types of weather may translate, in turn, in changes in the regime of the relevant variables.

Results

Figure 19 shows the 16 types of weather obtained in the influence area of Tegucigalpa, expressed as representative patterns of the spatial distribution of the STTI. The darker values represent the higher probability of generation of tropical storms; in the case of Tegucigalpa, most of the storms affecting the city are produced within patterns 1, 2 and 3. The synoptic patterns resulting from the analysis of the simulations of several general circulation models for future climate determine the probability of occurrence of hurricanes, as shown in *Figure 20*. It can be observed that the clearest effect of climate change in the area is the increase in the probability of weather type 1, without there being a material decrease in the probability of

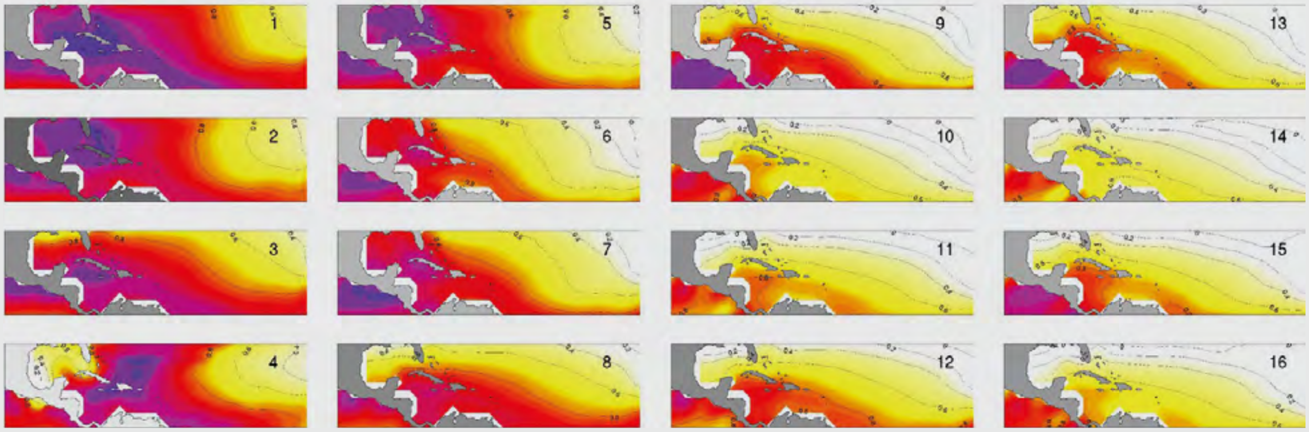


Figure 19 | SSTI (Sea Surface Temperature Index) representative patterns ordered according to their similarity. The purple color shows the areas where the SSTI is close to 1 and thus there is a bigger chance that cyclones be generated.

weather types 2 and 3; weather type 1 is characteristic of the month of September and also one of the types producing most hurricanes with influence in Tegucigalpa.

This result points at a higher incidence of hurricanes in the city during the next decades, which will predictably worsen the extreme rainfall regime.

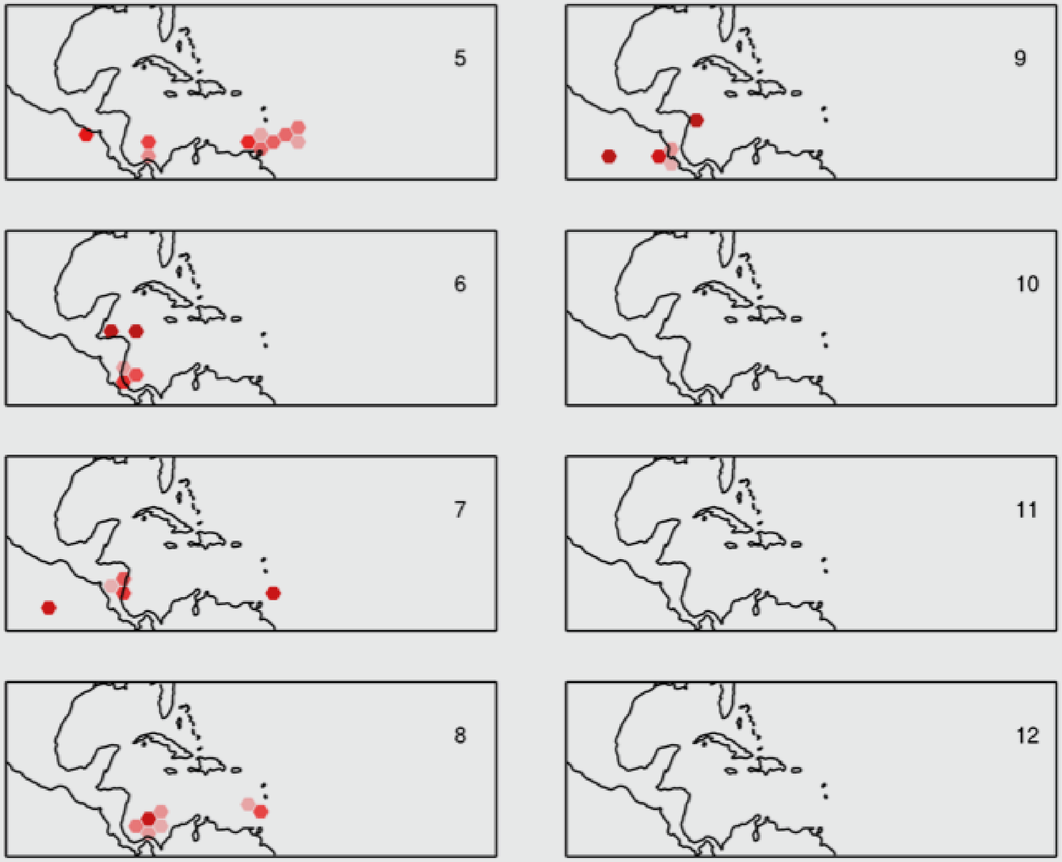


Figure 20 | Genesis of the tropical cyclones selected in each synoptic pattern of the SSTI.

Hurricanes and the El Niño phenomenon in climate change projections in LAC

Climate science and the associated climate models are a very active area of research and there are still many issues over which the experts do not agree. Two factors conditioning extreme phenomena in many LAC cities are hurricanes and the Southern Oscillation or ENSO (El Niño Southern-Oscillation); in both cases (but for different reasons) the general circulation models show discrepancies when projecting future trends. The El Niño phenomenon, probably the best known atmospheric teleconnection, is dominated by complex large-scale ocean-atmosphere interactions and shows a relatively long regularity (8-12 years), so there are no sufficiently long series of available instrument records. Global warming is expected to intensify the extreme events associated with this phenomenon (Cai et al., 2014), but it is very difficult to quantify their magnitude and translate it into the relevant variables for risks purposes (rainfall, wind, waves, etc.). This lack of knowledge, with the associated uncertainty, is directly transferred to the hazard variables included in studies about the risks affecting cities, not only in the Pacific areas of Colombia, Ecuador and Peru, but also in the Andean basins.

In addition, there is general consensus about the fact that global warming will lead to a higher frequency of generation of major hurricanes, in both the Atlantic and the Pacific ocean, and to a longer hurricane season; their tracks may change and they may reach higher latitudes (Walsh et al., 2016). It has also been detected that there is a relationship between the intensification of the El Niño phenomenon and hurricane generation frequency in the Eastern Pacific. Once again, the quantification of these effects in order to determine future risks requires more investigation and longer series of instrument data, so any projection needs to be treated cautiously and its scientific basis must be clearly presented.

Selection of a global emissions scenario

The climate change effect predicted by experts for different weather variables largely depends on the efforts of humankind to reduce greenhouse gas emissions during the 21st century, as well as on other factors such as land use management and forest conservation. In the Fifth IPCC report (IPCC, 2014), this group of factors is represented by what is called representative concentration pathways. There are four representative pathways, each one associated with an atmospheric concentration of CO2 equivalent for 2100. RCP 2.6 is the most optimistic scenario, RCP 8.5 is the worst-case scenario, and RCP 4.5 and RCP 6.0 are intermediate scenarios (see Figure 21).

In studies about the risks affecting cities, the selected RCP will decisively affect the future hazards and, therefore, the assessment of the necessary actions to reduce risks. Systematically adopting RCP 8.5 as a conservative measure may be very expensive in terms of the investments needed. As an alternative, an intermediate RCP (4.5 or 6) can be adopted for those risks whose associated reduction measures allow an incremental approach (e.g., the construction of a dam that can be expanded in case a more adverse emissions scenario materializes).

It should be pointed out that, in certain places, climate change produces and improvement in the hazard variables (e.g., fewer events of extreme rainfall). In this case, for purposes of being conservative, the concentration scenario to be adopted should be RCP 2.6, which implies a lower decrease in the hazard.

All in all, bearing in mind the above-mentioned aspects, the procedure applied in the ESCI to estimate the effect of climate change on the extreme regime of a hazard variable can be summarized in the following general steps:

1. Identify the target variable and analyze the available instrument records. According to the duration, location and quality of the available series, this information will be assigned more relevance or credibility. If long and reliable series are available, it is of great interest to analyze the non-stationary trends or patterns they may contain.

2. Identify the available climate databases with climate projections for the study area and different climate simulation models. At the very least, there will be global databases, and in some cases regional models too. In certain regions, it is recommended selecting the general or regional circulation models (GCMs or RCMs) that have proven to perform better. Each model provides results for different emission pathways (RCP), so at least two evolution scenarios may be considered (a more favorable and a more restrictive one, without them necessarily representing the two extremes).

3. Downscale the above mentioned projections to adjust them to the study area based on different methods, according to the available resources. In general, it is considered appropriate to use a statistical procedure – as is the case of ESCI and other similar studies. This type of statistical downscaling requires calibrating the general results of the models with available local data, as long as they are reliable enough.

4. Analyze trends in the local series. This is the last step and enables obtaining coefficients of climate change-induced transformation of the relevant variables for different time horizons, RCPs and evolution models. As previously discussed, the time resolution of the models will prevent answering some questions on the behavior of certain variables, such as short-duration rainfall, so supplementary hypotheses will be required.

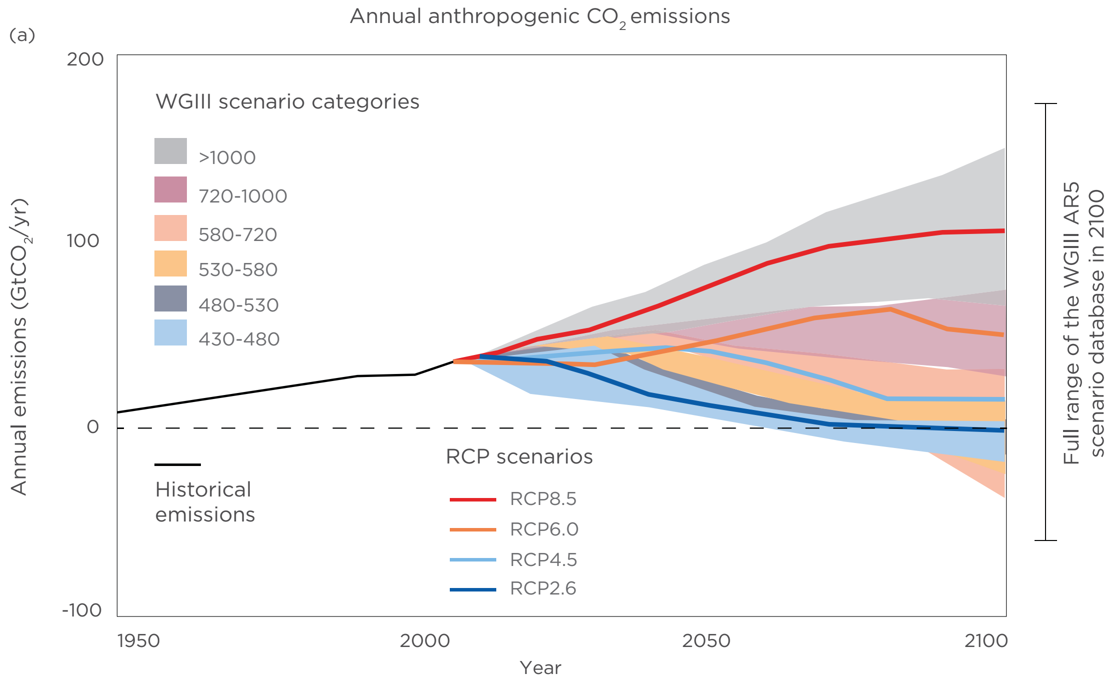


Figure 21 | Warming vs. accumulated CO2-eq emissions. The four representative concentration pathways (RCPs). Taken from IPCC 2014.

3

Vulnerability and flood risk —

3

3.1 Exposure calculation

Exposure is defined as the coincidence in space and time of a hazard and a receptor capable of being damaged due to such hazard. It is therefore a binary condition (a receptor is or is not exposed) that is necessary, but not enough, for risks to be produced; the exposure parameters reflect the maximum possible damage potential, which can be more or less close to the probable losses, that is, the risk. If the receptors are buildings, infrastructures, systems, equipment, etc., it is called physical exposure (Figure 22), whereas when it relates to people, it is called human exposure (Figure 23). The concept of exposure makes sense when applied to phenomena affecting specific areas in the territory, as is the case of floods, extreme winds (in areas with intensity variations) or even coastal erosion; for urban drought or wind in large plains or deltas, the exposure is equal to all of the existing assets and population.

In general terms, physical exposure refers to immobilized assets, which do not have the ability to move, although for practical reasons it often includes vehicles, domestic animals, and smaller items that can be movable. Therefore, they can be calculated by combining the hazard maps, for different probabilities of occurrence, with static maps that define the location and characteristics of the physical assets – including currently existing assets and assets projected for future scenarios. On the other hand, for the calculation of human exposure, given the mobile nature of receptors, the results can be incorrect if based on the static snapshot provided by demographic censuses, which

PHYSICAL EXPOSURE OF BUILDINGS	Exposed urban area (ha) Exposed built area (ha) Total exposure value (MUSD) Exposed surface area or exposure value by type of building.
PHYSICAL EXPOSURE OF CRITICAL INFRASTRUCTURE	Number of exposed elements by category Exposed surface area by category (ha) Exposed capacity by category (units change according to the category, see section 3.4)
HUMAN EXPOSURE	Total number of exposed people Number of exposed elderly, children and ill people Number of exposed people at risk of social exclusion

Table 6 | Most common exposure parameters.

do not account for the fact that certain city areas suffer great temporal variations in their occupation depending on their uses (residential, commercial, industrial, etc.). Such variations can be: daytime (pendular variations), weekly (business days versus weekends), and annual (festivals, particular events, seasonal activities such as fishing, winter sports, beach, etc.). Although it is necessary to set simplifying hypotheses and reasonable levels of approximation, it is convenient to bear in mind the dynamic character of human exposure in each case and not to unselectively adopt the census data to estimate it. The fact that people respond to a hazard with certain behaviors that are associated with response and evacuation patterns is not considered as an exposure factor in this document, but will be afterwards included as a vulnerability factor in risk calculations.

Table 6 includes some of the most common exposure parameters, but there may be others depending on the input data and the specific targets of each study.

It must be noted that some of the exposure parameters require information not only related to the assets and people, but also of a socioeconomic nature; although this information is not critical to calculate exposure, it will be essential to determine vulnerability, as shown in the following sections. All the parameters included in Table 6 may be expressed in a dimensionless fashion as indexes, among which the most commonly used are:

- Percentage of exposed population
- Percentage of the total urban area that is exposed.
- Percentage of the total value of the buildings stock that is exposed.

CALCULATION CONSIDERATIONS

Exposure parameters, with no further calculations, are sometimes used as estimates or even substitutes of risk parameters. However, the hazard intensity relationships are highly variable and may be misleading, since a high exposure level does not necessarily imply an equivalent high degree of damage, as it will be explained in the following sections, devoted to describing the other significant component of risk: vulnerability.

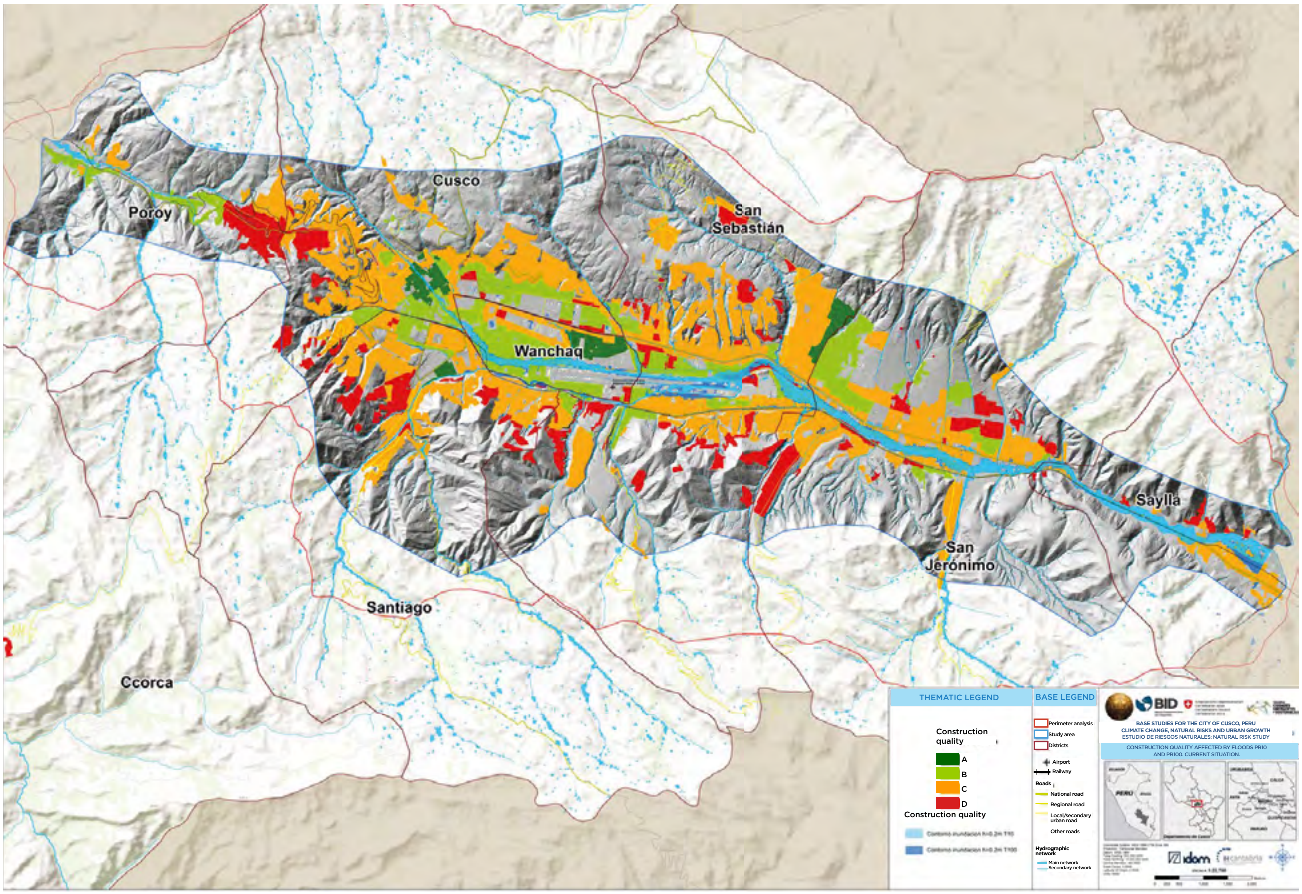


Figure 22 | Example of a map of physical exposure of buildings to floods in Cusco, Peru, according to their construction quality.

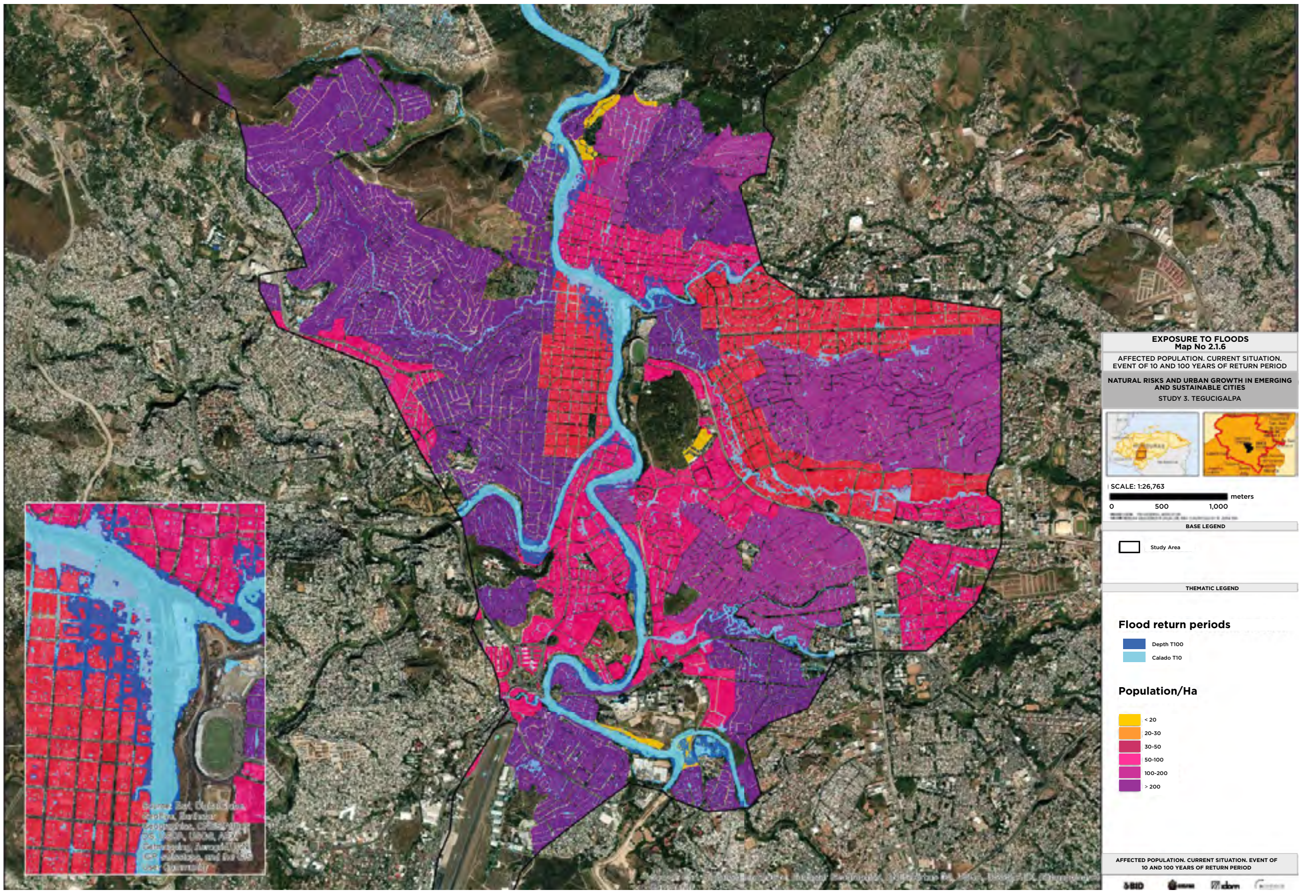


Figure 23 | Example of a map of human exposure to floods in Tegucigalpa, Honduras.

3.2 General considerations on the calculation of vulnerability

Vulnerability is a term used in multiple contexts with different meanings. In quantitative risk analyses, vulnerability refers to a lack of resistance or capacity of a building, infrastructure, or person to endure a hazard. For risk calculation purposes, vulnerability represents the element that enables the transformation of a hazard into damage through expressions that depend on both the parameters characterizing the hazard, and certain characteristics of the receptors. These expressions are usually called vulnerability functions or damage functions, and their results may be absolute or relative damage values (percentages of damage in relation to the total exposed value). This document will focus on the latter type of damage functions, i.e. dimensionless, since they require less detailed data of each city and are easier to extrapolate between different places. However, the general methodology to calculate damage is not affected by the choice of damage function; provided there is local information on the value of the assets, as well as experience recording actual damage, it is advisable to adopt the approach involving functions in monetary units.

To arrive at the concrete expression of a dimensionless damage function for a specific risk, it is necessary to determine what is(are) the dominant damage mechanism(s) associated with such risk in the area under study. A damage mechanism is defined as a sequence of specific physical processes that cause a hazard to turn into actual material or human losses.

While several potential damage mechanisms can be identified for floods, only some of them will be present in each concrete case of study. The following are some of the most common economic damage mechanisms for buildings, associated with floods:

- Deterioration of assets due to a water level rise in buildings, without structural failure.
- Destruction of buildings due to wash-out, including impacts from floating elements.
- Collapse of walls due to water load.

Similarly, different common mechanism of human damage can be identified:

- Drowning due to being subject to extreme flow conditions.
- Dragging, falling and impacts due to flow conditions.
- Dragging of vehicles with people inside.
- Freezing as a consequence of staying in or outside water during long periods of time at a low temperature.

The selection of a concrete damage mechanism, representative of a certain risk in a city or area under study, entails the following decisions, which thus depend on such selection:

- **The relevant hazard characterization parameters:** in a slow flooding of the interior of a house, the water elevation is the parameter that is most related to the damage caused. However, when water flows quickly, the dragging capacity will depend on a combination of water speed and flood elevation, with the earlier being at least as important as the latter.
- **The classification of the assets for which risk is analyzed:** according to the selected damage mechanism, it will be important to differentiate the exposed assets according to some or other characteristics. For slow flooding with no speed, it is of little relevance to know the structural quality of the buildings, but it is essential to know the number of stories and if there is a basement;

on the other hand, when it comes to dragging, good quality dwellings with solid foundations and good structural materials will be less vulnerable than poor quality constructions.

- **The group of assets that can be damaged, whose value must be multiplied by the result of the dimensionless damage function:** referring to the previous examples, for slow flooding of a house, water may deteriorate a part of the total value (systems and equipment), but the structure is reusable; if there is a risk of dragging and impact, then the whole asset is at risk, that is, the container and the contents.

Dimensionless damage functions usually include the hazard characterization parameters as variables that are independent from the expression that defines them, since they are usually positive continuous variables (flood elevation, water velocity, wind speed, etc.). However, since we are dealing with discrete and not scalable categories (concrete buildings, substandard houses, etc.), the types of assets for which damage is assessed are usually incorporated by modifying the form of the damage function, that is, by adopting an expression for each category of receptor.

CALCULATION CONSIDERATIONS

It is useful to have the damage functions related to a specific mechanism in the form of a family of functions, possibly piecewise, with an explicit analytic expression. Such family will have two types of input parameters: those characterizing the hazard, and those defining the type of asset to which the function is applied. The latter will be tabulated for each category of asset considered.

Finally, the total value of the assets at risk, which also depends on the damage mechanism, is incorporated as a factor that multiplies the dimensionless damage function, so it will be addressed in the section related to damage estimation. If multiple mechanisms are identified, the damage associated with each of them may be treated as additive, as long it affects differentiated assets (e.g., extreme wind damages the roof of a house, while the water level inside damages its systems). Otherwise, if different mechanisms compete to depreciate the same asset, supplementary hypotheses should be assumed, as shown further below.

Very commonly, the concept of damage mechanism is considered as directly equivalent to a risk type, assuming there is a biunivocal relationship between them and they are thus redundant terms. Although in practice this may be true in many cases, the consideration that within a certain type of risk there are multiple possible damage mechanisms that should be evaluated beforehand enriches the vulnerability analysis. Based on the conceptual framework described, criteria can be established for any type of damage from any hazard, once the dominant damage mechanisms have been defined. The following sections include a description of the damage functions available for the different types of assets and damage mechanisms, with their related properties and potential calibration methods.

3.3 Vulnerability and damage to buildings

This section will describe a procedure to quantify direct damage to buildings from floods, extreme winds, and coastal erosion, within the framework of a project like the ESCI. Given the need to make projections about future damage considering the effects of climate change, as well as the possible evolutions of the urban patch, it is convenient to propose a classification of building types in a city considering a reduced number of categories, but including the characterization of the most important distinguishing features of the exposed elements.

Based on the current urban patch, with the most recent cadastral and census information, and after conducting field inspections to check such information, it is necessary to make a classification of the dominant building type in each unit – usually a block. It is often sufficient to define a certain number of building typologies (usually between three and five), which usually have a high correlation with the socioeconomic level of their inhabitants, although other processes also affect them; if four types are adopted, by convention they will be named A, B, C and D, in order of highest to lowest quality. This classification will be the basis to designate the damage functions related to each category and damage mechanism, as well as to project urban growth scenarios. Please note that, although in the current situation it is possible to make a more detailed disaggregation of building typologies, such a level of detail makes no sense when analyzing future situations, where it is only possible to predict – using due caution – general growth patterns.

For each type of analyzed risk, with its damage mechanisms, there will be a reclassification of the base building typologies (A, B, C, and D) so that a biunivocal relationship can be established between such reclassified categories and the appropriate damage functions.

Relative damage from flooding

For flooding risk, it is usual to consider two damage mechanisms called slow flooding (without structural collapse) and fast flooding (with potential structural collapse).

In slow flooding, the form of the damage function depends mainly on the vertical distribution of the assets at risk, so the four basic categories can be translated into a characteristic storied-structure, for example:

- **Category A:** Dwelling with more than two floors and a basement.
- **Category B:** Dwelling with two floors, without a basement.
- **Category C:** One-story dwelling with a resistant roof, without a basement.
- **Category D:** One-story dwelling without a resistant roof and without a basement.

With these hypotheses, it is already possible to resort to a local or generic database (such as the ones offered by CAPRA or HAZUS) to select the relevant damage functions (see an example in Box 6).

As for fast flooding, the phenomenon under consideration is the total destruction of a building caused by moving water and dragged material (debris), and the hazard characterization variables are flood elevation and water velocity. In this case, it is difficult to establish damage functions for each basic category, since it would imply considering the material and structural typology of the foundations, walls, roofs, etc. However, a simple collapse criterion can be adopted for type D dwellings, which are the most precarious (often related to informal settlements) and usually located in the most conflictive places.

When the collapse criterion is met, it is considered that the affected dwellings lose their full value, whereas below such criterion, the slow flooding mechanism applies. It is important not to double count damage – when there is a collapse, the value exposed to the effects of slow flooding becomes null.

In this way, an approximate answer is given to a question of high concern in cities with depressed areas, which are commonly found in LAC: how many people can become homeless and in need of social assistance if a natural disaster of a certain scale strikes.

Relative damage from wind

In order to calculate wind damage, an approximate procedure similar to the one already described can be applied, with two essential damage mechanisms:

- Partial progressive destruction of a building, starting from its roof and spreading to the higher floors.
- Tearing up and total destruction of a building due to extreme winds.

In the first mechanism, the basic categories must be reclassified according to the typology and anchoring system of the associated roofs:

- **Categories A and B:** concrete roof, brick walls, two or more floors.
- **Category C:** light roof, masonry walls, one floor.
- **Category D:** light roof, non-bearing walls, one floor.

Again, the CAPRA and HAZUS databases provide numerical expressions to quantify the relative damage associated with each of the above setups, based on the peak wind speed, when there is no local information on historical disasters. The collapse criterion – again very difficult to establish rigorously for all typologies – can be simply defined through a wind threshold (e.g., 200 or 250 km/h) for Category D dwellings.

Relative damage from coastal erosion

Coastal erosion is a relatively slow process, compared to floods and extreme winds, which can produce the deterioration and collapse of coastline buildings. However, due to the large number of factors (hydrodynamic, geotechnical, structural) involved in this phenomenon, there are no simple and accepted damage functions to quantify it. Potential erosion rates, as quantifiers of the hazard, do not often translate into actual risks due to the presence of protective structures such as walls, breakwaters and fillings, making actual damage usually lower than expected. A large proportion of the urban coastlines exposed to erosion processes have been hardened through structural elements (as it is the case of cities participating in the ESCI like Georgetown, Campeche, Belize, Cumana, and others), which does not prevent flooding and other problems like beach loss, but does prevent structural damage due to shoreline recession. However, coastal erosion not limited by coastline protection works can have significant economic and, particularly, human implications in disadvantaged rural areas.

In practice, if there are coastline protective structures, erosion damage in adjacent properties is insignificant (unless such structures are at evident risk of collapse), and the risk is limited to flooding from sea and wave overtopping. For unprotected stretches of coast, erosion implies a full loss of the property value, including that of the land itself that disappears.

Assets at risk and absolute damage calculation

Damage due to an extreme event in each calculation unit – usually a block of buildings or an urban sector – can be obtained by multiplying the result of the dimensionless damage function by the relevant value at risk; total damage results from the application of this procedure to the entire urban space. At this final step in the calculation, is remains to define what is the value at risk related to each type of risk and damage mechanism, and how this value can be estimated from the available data. The upper shaded line on Table 7 shows the four large categories of assets that jointly determine the total value of a building:

<table>
<tr><th>LAND VALUE (LV)</th><th>CONSTRUCTION VALUE (CV)</th><th>SYSTEMS VALUE (SV)</th><th>EQUIPMENT VALUE (EV)</th></tr>
<tr><td></td><td colspan="2">DV: Dwelling Stock Value</td><td></td></tr>
<tr><td colspan="3">MV: Real-estate Market Value</td><td></td></tr>
<tr><td></td><td colspan="3">VRC: Value at risk in the event of collapse (flooding or windstorm)</td></tr>
<tr><td></td><td></td><td colspan="2">VRNC: Value at risk in the event of slow flooding or wind without structural damage</td></tr>
</table>

Table 7 | Types of value, for purposes of applying the different dimensionless damage functions, according to the type of assets they comprise.

1. **Land Value (LS):** the urban space where a building is located is an economic asset of a singular nature because it is unique (each plot is different), indestructible (the land, not its market value), and it has an infinite lifespan, so it does not depreciate over time (although this does not prevent it from suffering considerable price fluctuations).

2. **Construction Value (CV):** it is the value of the building itself, including the structural elements like foundations, pillars, beams, walls, slabs, roofs, etc. The construction value depends mainly on the availability of construction materials and on labor costs.

3. **Systems Value (SV):** it includes pipelines, cables and other equipment related to drinking water supply, sanitation, electricity, gas, telephone, heating and other services inside a building.

4. **Equipment Value (EV):** it includes the rest of the elements in a house or building that are not included in the previous categories and that are largely mobile: furniture, electrical appliances, electronic devices, jewelry, paintings, etc. For convenience, the vehicles related to private dwellings can be included in this category.

This classification is not useful in the application of damage functions, so it is convenient to define other four types of values that comprise a certain combination of the above categories of assets:

1. **Dwelling stock value (DV):** it is the replacement value of buildings and their related systems, without including the value of land and equipment. It is equivalent to the construction price in the construction market, considering it independently from the land market, to which it is usually related.

2. **Real-estate Market Value (MV):** it is the market value of a certain building, which includes – in a hardly separable way – the value of the land where the building stands.

3. **Value at risk in the event of collapse (VRC):** it is the replacement value of the set of assets that can be deteriorated when a building suffers structural damage, that is, its container (structural elements and systems) and its contents (equipment) are damaged. There is necessarily not a loss of land value, but if there was, it would be treated as an indirect damage, which is not reflected by damage functions.

4. **Value at risk in the event of slow flooding or wind without collapse (VRNC):** it is the replacement value of the assets that can

be damaged when water or wind enters a building without altering its structural elements.

For damage mechanisms due to slow flooding or moderate winds with no structural collapse, the dimensionless damage functions must be multiplied by the VRNC, whereas in the case of structural damage (complete or partial), the variable that is destroyed is the VRC. The dwelling stock values and market prices are useful as possible ways to estimate VRC and VRSC, since these values are not available in most cases.

The dwelling stock value is useful due to its correlation with the GDP of a city, and it can be afterwards broken down into socioeconomic categories adopting a known income distribution (e.g., a Pareto distribution) whose standard deviation is a direct function of the Gini index or other inequality parameter. This macroeconomic approach is relatively simple and fast to apply (once we have the classification by socioeconomic category) and its error margin is usually small. Once the DV has been established, two additional hypotheses – for which there is often a certain empirical basis – must be adopted:

- The value of the systems in relation to the total value of a building (coefficient c1).
- The average total value of the equipment in relation to the total value of a building (coefficient c2).

In general, different values may be specified for coefficients c1 and c2 for each socioeconomic category (A, B, C, and D) of buildings.

Another procedure to estimate the VRC and VRNC is to find out the land values in the real-estate market and, based on some empirical criterion or the land markets, disaggregate the portion related to the land from the portion related to the buildings themselves. The difference between the market value and the land value is, again, the above-mentioned DV value, so the next steps to obtain the values at risk are the same. This is a more burdensome approach because it involves fieldwork. This bottom-up approach may lead to unrealistic values, especially if there is not a good representation of the real estate market in all social classes. It is advisable to combine both methods, if possible, trying to understand and bridge their differences.

As a summary of the preceding paragraphs, the following simple expressions compile the proposed workflow to obtain the values exposed to direct damage in VRNC (no structural damage) and VRC (with structural damage) buildings, which must multiply the dimensionless damage functions:

- **Method 1:**

1. Hypothesis and field data to calculate LV and MV
2. Obtaining DV=MV-LV

- **Method 2:**

1. Macroeconomic and income distribution data to obtain DV.

- **Both methods:**

1. Hypothesis or field data to calculate factors c1 and c2
2. Calculation of SV = c1·DV
3. Calculation of EV = c2·DV
4. Calculation of VRNC = SV+EV· (c1+c2)
5. Calculation of VRC = DV+EV=DV· (1+c2)

BOX 6 —

Estimation of economic damage from floods in Xalapa (Mexico)

Problem

Light or moderate rainfall is common in the metropolitan area of Xalapa, at least since the second half of the 20th century. These events affect roads, shops and dwellings in Xalapa, Banderilla, and other adjacent municipalities. The frequency of pluvial floods has increased during the past years without it being caused by an increase in the rainfall regime; it is the urbanization processes and human activity that has probably intensified this type of problems.

Methodology

In order to quantify economic damage from floods in the city of Xalapa, the urban physical vulnerability has been characterized (degree of impact that the hazard can have on the exposed elements) and represented by a function that sets a relationship between some intensity parameter of the hazard and the potential damage.

The physical vulnerability functions have been based on the library of vulnerability functions proposed by the software tool ERN-Vulnerability (www.ecapra.org) and are divided in the following categories:

Damage functions for buildings

The allocation of functions is defined for each building typology: low-quality, standard, and above-standard. In this case, they have been grouped in two types, since in the Xalapa floods water velocities are low (except inside river channels) and, therefore, no building collapse is produced.

The damage proportion depends on the existence of one or more functional levels in the dwellings. For the most fragile dwellings, it has been assumed that there is no second floor or that the second floor is the roof itself, so it does not have load bearing capacity (type 2); in turn, for medium or lower fragility dwellings, it has been considered that the existence of upper floors helps protect a larger proportion of the assets at risk (type 1).

Damage functions for critical infrastructure

The allocation of damage functions to critical infrastructure (CI) is defined by the category under analysis (public administration, water and sanitation, energy, industry, transportation, education, medical assistance, and commercial) and five function groups have been established (A, B, C, D and E). Additionally, a quantification has been made of the services impacted by the loss of functionality of the affected infrastructure elements. The damage and functionality loss curves, defined through expert judgment, intend to capture the basic phenomena that characterize flooding.

Assessment of economic damage

1. **Direct economic damage to buildings:** It has been obtained by applying the already-described vulnerability curves to the types of dwellings found in the area, taking into account the flood elevation reached by events with different return periods.

2. **Direct economic damage to CI:** It is obtained in the same way as the economic damage to buildings, that is, through the application of the vulnerability curves.

3. **Indirect economic damage to CI:** The objective is to obtain, through shadow

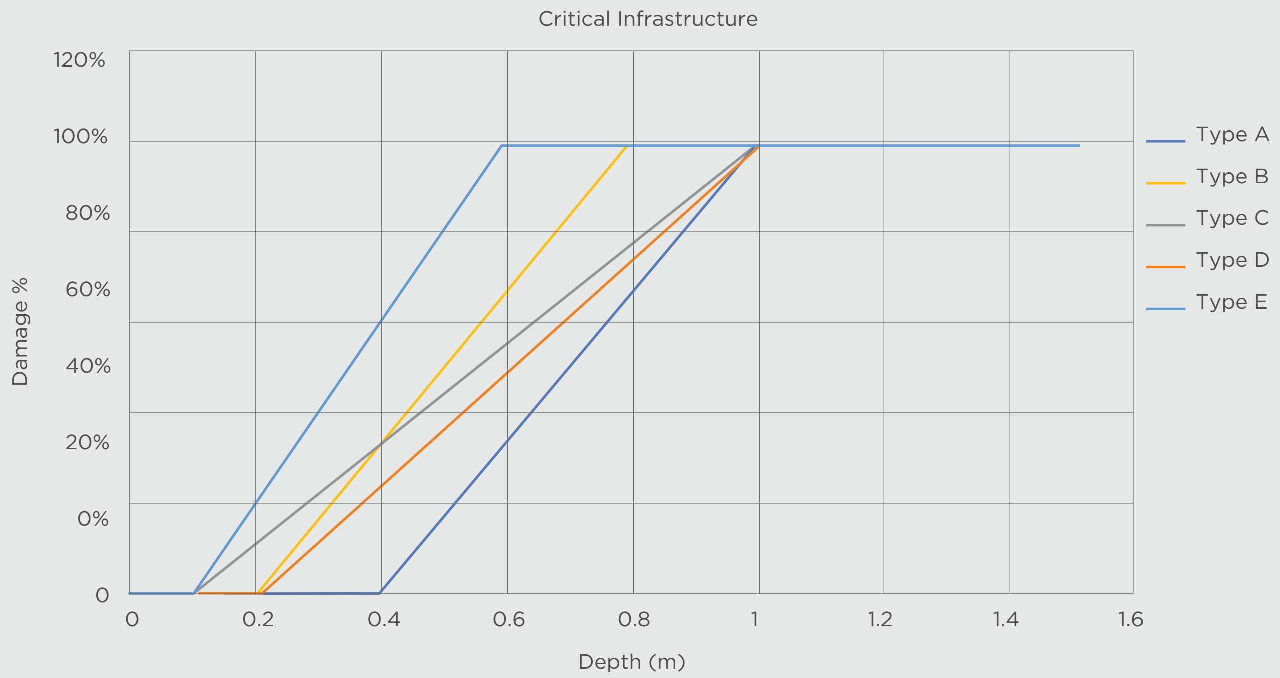


Figure 24 | Loss of service functions.

prices, the economic damage derived from the interruption of a service to which each critical infrastructure is linked by using functionality curves, which relate water elevations to the loss of service involved.

Results

Most of the economic damage that has been quantified is direct damage related to the entry of 0.5-1 m of water into dwellings and shops during a short period of time (a few hours), with indirect damage being nearly insignificant, at least at present.

Direct damage to buildings is distributed throughout the territory in a scattered fashion, so it cannot be affirmed that it is associated with a local problem. The floods that take place in Xalapa are sometimes sudden reappearances of ancient river channels that have been erased by the urban footprint, without there being an underground stormwater network to collect at least part of the surface runoff in the instants of greatest intensity. The urbanization of peripheral areas in the city has also increased the risks in more centric areas that traditionally did not suffer floods, or where floods where less intense.

As regards damage to critical infrastructure, some of the essential sub-systems that support the urban metabolism are partially affected by the effects of a flood. Indirect economic damage is lower because there is no long-lasting loss of functionality in buildings or critical infrastructures due to most of them being located outside the areas exposed to this phenomenon.

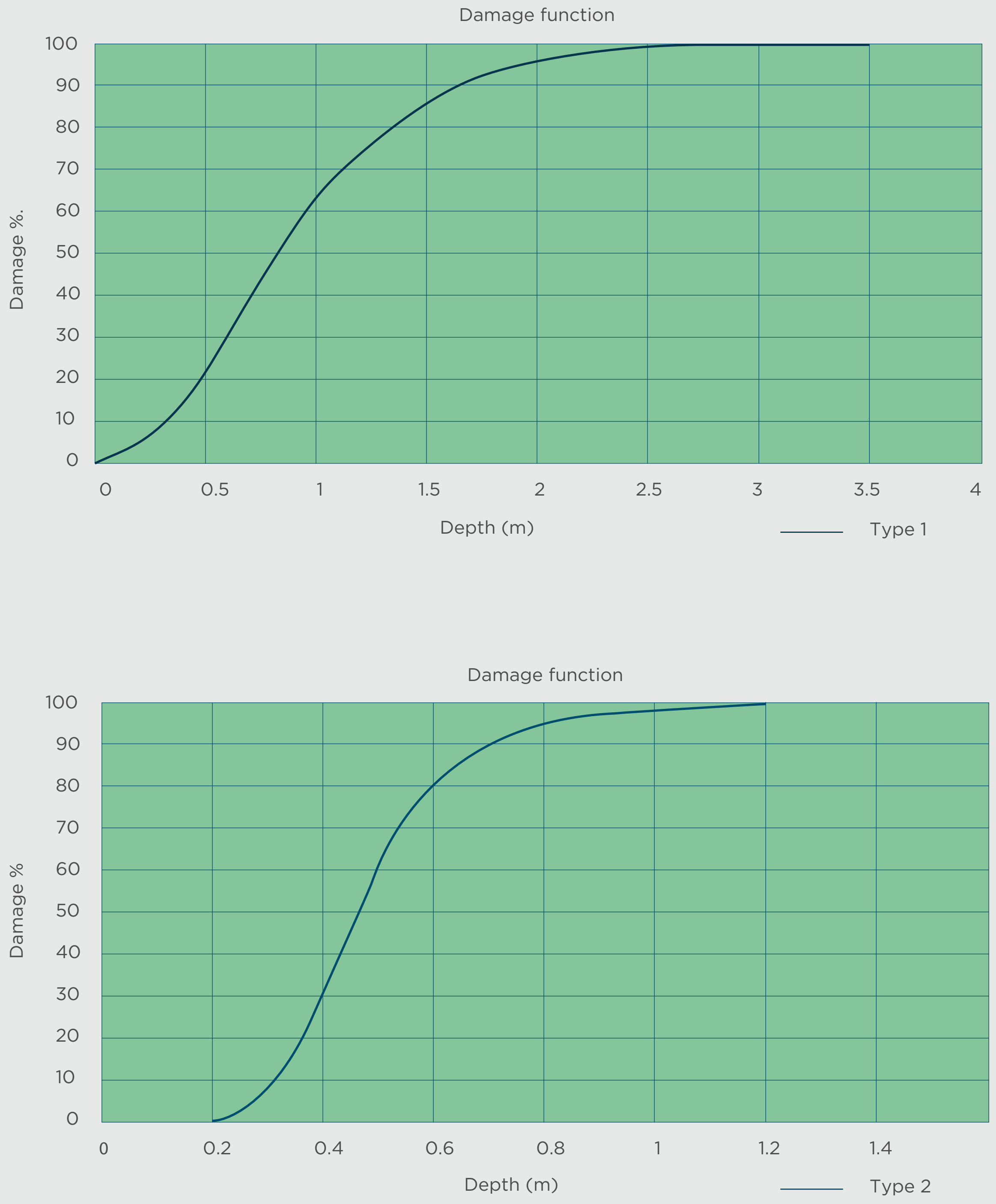
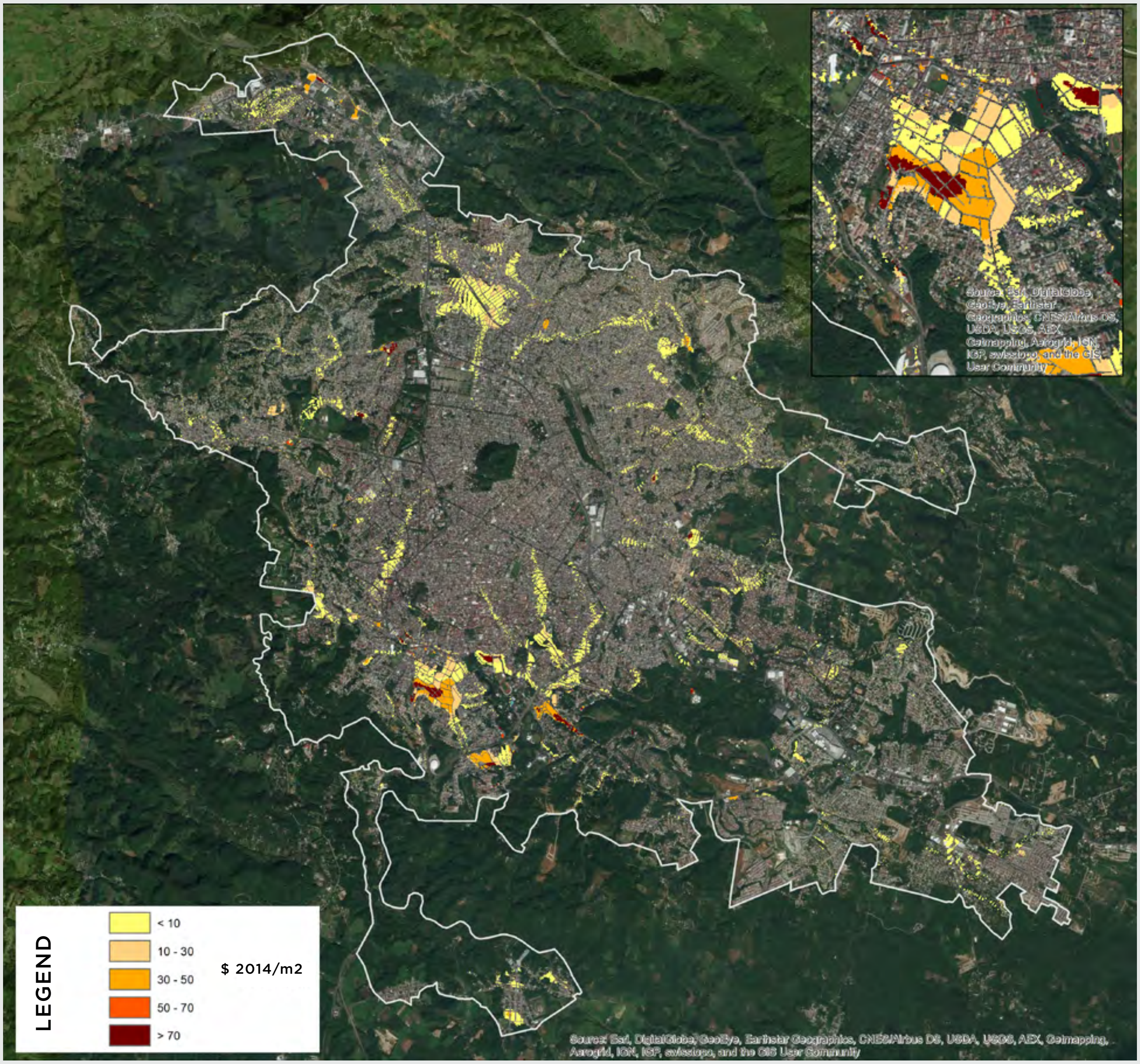


Figure 25 | Damage functions to calculate flood risks



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 26 | Economic damage from floods in Xalapa (Mexico) for a 10-year return period.

Exposure is defined as the coincidence in space and time of a hazard and a receptor capable of being damaged due to such hazard. It is therefore a binary condition (a receptor is or is not exposed) that is necessary, but not enough, for risks to be produced; the exposure parameters reflect the maximum damage potential, which can be more or less close to the probable losses, that is, the risk.

3.4 Vulnerability and damage to critical infrastructure

In the context of this document, critical infrastructure are physical elements that, apart from having an intrinsic economic value (replacement value) that may be damaged, perform a key function in one or more subsystems of the urban metabolism (Kennedy, Pincetl and Bunje, 2011) and, therefore, their functionality loss implies a more or less permanent alteration of the normal functioning of a city, which translates into indirect damage.

The general problem of estimating the indirect damage related to a specific natural hazard is very complex and requires an ad hoc approach in each case under study, based on detailed information on the flows of people, matter, and energy that take place in each city, including their interrelations. As a first approach to the problem, a simplified method will be outlined to analyze the systemic vulnerability of a city to a certain rapid-onset risk, like floods or hurricanes, which is valid for studies with a similar scope to those conducted under the ESCI.

The following are the main hypotheses of the proposed method, which make it generally applicable with a reduced (though not insignificant) amount of information:

1. A limited number of subsystems that are representative of the urban metabolism and relevant to the risk to be analyzed are defined. For each subsystem, a characteristic flow unit is determined. Each subsystem is analyzed independently from the rest disregarding their interactions.

2. Although each subsystem is characterized by a group of nodes and links as a graph, the analysis focuses on the nodes, giving less importance to the flows connecting them. This way, the analysis of the networks is avoided, assuming that its functioning depends on the integrity of the nodal elements that make it up.

3. Each flow unit representative of each subsystem is assigned an average shadow price. These prices, combined with an estimate of the duration of the interruption due to the disaster (return to normality time), are used to obtain an economic value of the indirect damage to each subsystem and to the group of subsystems.

Table 8 shows the generic subsystems that have been used to characterize the metabolism of different cities that were part of the ESCI, with their related representative flow units.

The main steps to apply the proposed method to a specific city are the following:

1. Identification, delimitation, and classification of critical infrastructure according to the categories shown in *Table 7*, or others deemed convenient. All the information will be grouped in the same map database.

2. Crossing of the above-mentioned information with the flood marks associated with different return periods (usually 10 and 100 years, as representative events) to determine the flooded area and the average flood elevation in each critical infrastructure. The procedure is conducted in a GIS and entails overlapping the critical infrastructure layers and the flood elevation for the return period under consideration and, based on that, working with rasters using the selected damage functions.

3. Assigning an economic replacement value and a functionality to each critical infrastructure. This can be done either by using actual data, based on information that is specific of each city, or by calculating the total capacity of each subsystem (for instance, the total school

population, in the education subsystem) and assigning to each element (school/ day care/academy) a functionality that depends on its size, represented by its plan surface. While it is better to know the actual capacity of each school instead of estimating it from the building size, and the same applies to the other subsystems, sometimes the effort required is not outweighed by the apparent increased accuracy, in the context of a simplified method.

SUBSYSTEMS	FLOW UNITS
SANITATION	Wastewater production (m3/day)
SUPPLY	Drinking water consumption (m3/day)
MEDICAL CARE	Patients seen per day
COMMERCIAL	Commercial expenses (MUSD/day)
ENERGY	Energy consumption (MWh/day)
INDUSTRY	Industrial production value (MUSD/day)
URBAN SERVICES	Average daily users
EDUCATION	Average daily students
TRANSPORTATION	Travelers per day

Table 8 | Most common subsystems to characterize the urban metabolism and their related representative flows.

4. Adopting a family of physical and functional vulnerability functions (service loss) for each subsystem. Physical vulnerability functions, similarly to buildings damage functions (section 3.3), indicate in a dimensionless fashion the direct damage derived from a certain hazard (e.g., the destruction of systems and equipment in a school due to flooding). Functional vulnerability functions represent the same concept, but in terms of the impact on the capacity of an infrastructure to provide the relevant service within the subsystem it belongs to. In a simplified framework like this one, the graph of such functions take the shape of a step or ramp, with a 100% functionality below a certain hazard threshold and no functionality above another value (see Figure 22)

5. By applying the foregoing physical and service damage functions to all critical elements, once they have been assigned an economic value and a capacity, we obtain a direct loss (in monetary units) and a functionality loss (in flow units) for each element, by subsystem, and combined for the entire city.

6. Finally, by adopting a representative shadow price for the flow unit of each subsystem and a characteristic duration of service interruption (usually weeks), which can depend on the intensity of the event, it is possible to translate the effect of the functionality loss into monetary units, which ultimately represents an approximation to indirect damage.

When following the previous steps, the capacities of each subsystem and the shadow prices of the related flow units are the two most difficult variables to obtain or estimate. If there is no local data specific to each city, the statistics – which are generally on a country scale – provided by international organizations such as the World Bank, UNPD, UNICEF, OECD, WHO, WTO, etc. have proven useful.

For some of the indicated subsystems, like urban transportation, the hypothesis involving only considering the nodes (in this case, transportation terminals and perhaps bridges) is very restrictive, since the main impacts on traffic are usually related to the flooding or loss of functionality of main roads, with the consequent reorganization of circulation patterns. Whenever possible, this problem should be addressed through a network approach. In addition, the interrelation between the different subsystems is usually a key factor in the management of emergencies and, within the proposed method, it should be analyzed qualitatively based on the results obtained for each individual subsystem. For example, a collapse of the transportation network may block the access of police officers and firefighters to the emergency areas in spite of their being on active duty; similarly, an energy outage will halt the industries in the area, even if their premises have not been directly affected.

Ultimately, the method described represents an extremely simplified approach to the problem of determining the indirect damage derived from a disaster, and in no case can replace a more exhaustive analysis, which will in turn demand more time and resources. However, it has been demonstrated that the information provided by this prospective method (regarded as semi-quantitative) is useful to explore the systemic risks of a city, as well as to compare the seriousness of these risks across different cities.

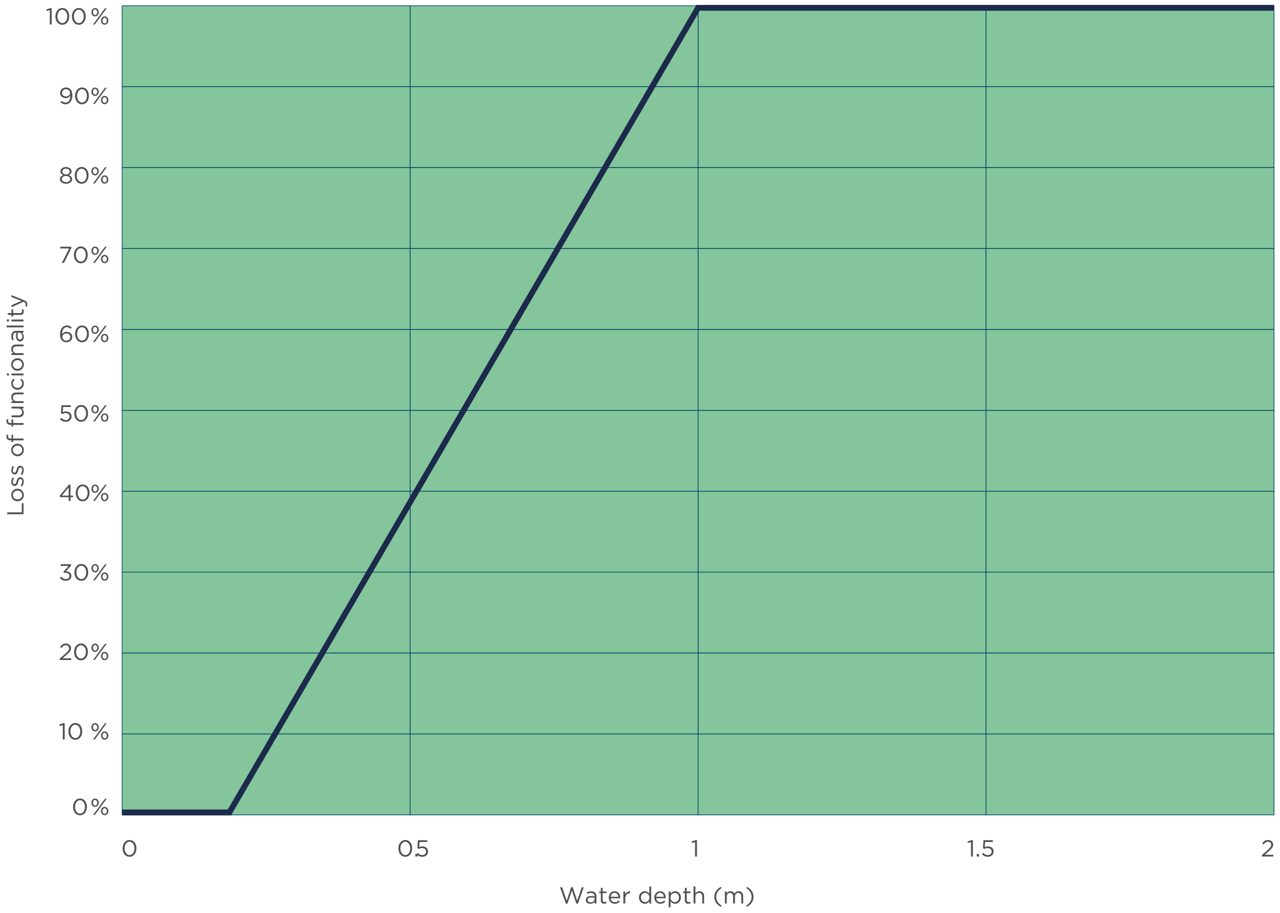


Figure 27 | Example of functional vulnerability function for a public building

3.5 Vulnerability and human damage

Beyond material losses, natural disasters may cause severe and long-lasting physical and mental damage to the people living in cities, limiting development options in the most basic sense, especially for the most disadvantaged citizens. One of the most widely used indicators of human damage is fatality associated with a certain type of risk, understood as the average number of deaths per year. It is also useful to know the average number of people that, as a consequence of a disaster, will be deprived of a home permanently or for a certain period of time and will, therefore, need a shelter. Finally, the population affected by a certain type of risk, including all the people living or developing their daily activities in areas that are exposed to a hazard (e.g., floods with more than 0.3 meters of water depth), although strictly speaking this is not a hazard but an exposure parameter, can be added to the risk indicators because it provides information on the population that can suffer deferred physical and mental health damage.

The following are rapid methods to estimate these parameters in the different types of risks, except for urban drought, which, due to its particular characteristics, is analyzed independently.

Relative damage from flooding

In order to estimate the average number of deaths associated with a certain flooding event, of whatever nature, it is necessary to determine the dominant damage mechanisms, which – as a first approach and for calculation purposes – are two:

1. Death by drowning or from heart attack in deep waters with low or moderate flow velocity.
2. Death by drowning, contusion or dragging in areas with preferential flow or waves.

The separation between these two mechanisms (which also includes other possible intermediate mechanisms) is established according to binary criteria involving water velocity and level. Once the dominant damage mechanism is established, the hazard characterization variables are determined: elevation for slow flood, and a certain combination of depth and velocity for fast flow. Finally, formulas previously adjusted based on data of historical disasters (particularly hurricane Katrina, in 2005) provide, even with confidence levels, the average death tolls for each hazard level (Jonkman, Vrijling, and Vrouwenvelder 2008).

These formulas for fatality from flooding should not be applied to the whole of the exposed population in the static sense described in section 1.3.3.c, but to the population at risk (PAR), understood as the fraction of the total population that could not be evacuated, either in the horizontal sense (towards non-floodable land) or in the vertical sense (access to non-floodable floors in tall buildings). The efficiency of the evacuation process depends on different factors including:

- Risk perception and awareness.
- Existence of an evacuation plan.
- Efficiency of the warning system within the evacuation plan.
- Traffic congestion.
- Warning time.

Ultimately, if seeking a simple approximation to human damage, a flow exposure factor (FEF) for each work unit should be determined in order to be able to determine the associated population at risk, to which the fatality formulas apply. The FEFs depend on the vertical structure of the buildings in the study area (which determines the vertical evacuation options), as well as on the above-mentioned factors. In areas with category D dwellings (low quality and one floor), the FEF is usually around 10% when there are no nearby high areas that may provide protection, whereas in wealthier neighborhoods, with better quality and tall buildings apart from single-story buildings, the population actually exposed to the flow is usually less than 1%. These approximate values have been obtained from the calibration of concrete events in cities that were part of the ESCI, but they need to be reviewed in each case.

As regards the estimation of the people in need of shelter, as an initial approach, it is proposed to count the number of people censed in areas where the building collapse criterion is met, as described in section 3.3. *Box 7* shows an example of the application of this methodology in the city of Santiago de los Caballeros, in the Dominican Republic.

Human damage due to extreme winds

Extreme winds, like floods, can produce considerable human damage, which can be simply expressed as the loss of lives and the generation of people with shelter needs. As an approximation to fatality from winds, a possible approach is to consider an average fatality rate, of about 10% according to some empirical analyses, for people censed in buildings that experience an advanced degree of structural damage as a consequence of this phenomenon. In order to calculate the expected number of deaths, first it would be necessary to determine what are the buildings with severe structural damage and, based on that, quantify the population at risk. As an intermediate result of these calculations, the number of people losing their home and therefore needing temporary shelter is also obtained.

Human damage due to coastal erosion

Considering it is a process of relatively slow onset, conditioned by the existing coast defensive structures, coastal erosion in urban areas does not usually produce, at least on a large scale, human damage in the form of dead or injured people. However, in recently occupied areas, generally of a low socioeconomic level, the buildings located along a receding coastline can suffer deterioration or collapse if no defensive walls or breakwaters are built due to lack of time or resources. To quantify this risk in human terms, an analysis of each specific case should be conducted, but as a first approach, it can be assumed that there is enough time to evacuate people, although their dwellings will become unrecoverable and all the people affected by this circumstance will be in need of a shelter.

Considerations on vulnerability and deferred human damage

Damage due to a catastrophic event may be produced during or after the event, with very diverse and complex developments deferred in time. Although most of the damage to buildings happens during the critical period of the hazard, damage to public infrastructure usually persists over months or years through its systemic effects (see sections 3.3 and 3.4). To an even greater extent, human damage is not limited to deaths by drowning or impact during the most critical periods, but can persist for a long time in the form of water-related diseases (see Box 8), malnourishment, and all kinds of psychological damage derived from an incapacity to overcome a tragedy.

The attributes determining human vulnerability in a broad sense are difficult to quantify and are usually related to poverty indexes. Aspects like disaster preparedness and resilience are increasingly attracting the attention of experts within a more proactive, systemic and continuous paradigm of risk management, as opposed to the traditional cycle of disaster-reaction-oblivion. The risk management cycle that characterizes the new approach redefines the stages and re-stabilizes the actions associated with each stage, which in the traditional cycle would be concentrated on the post-disaster period:

1. Preparedness period: it accounts for most of the time, when the institutions, as well as the communities of neighbors and even individual households must work in

an orderly and efficient way to plan the protocols and actions associated with the rest of the phases. Investments must be made in informing the population on the risks to which they are exposed, and outreach efforts should be promoted. This period also includes conducting studies and preventive actions to reduce risks.

2. Warning period: this period exists because its existence has been previously planned and organized, and because early warning systems capable of reaching most of the population within an adequate period of time have been implemented. Different protocols can be activated – e.g. evacuation protocols.

3. Disaster and immediate response: the efforts made cannot prevent disasters from happening, but can certainly enable the setting of fast response protocols for implementation during the most critical times, and immediate rescue tasks can be carried out as soon as the hazard subsides. It is also necessary to contemplate the provision of basic assistance to the evacuated and damaged people during a certain period of time. Essential public services (water, energy, communications) must be restored as soon as possible.

4. Deferred response: certain physical and psychological reconstruction actions cannot be carried out immediately, as they require a time-extended approach, usually over several years, depending on the scale of the tragedy. This phase can overlap or even blend together with the restart of the cycle and the beginning of the new preparedness period.

These aspects are analyzed in greater depth in Chapter 6.

The general problem of estimating the indirect damage related to a specific natural hazard is very complex and requires an ad hoc approach in each case under study, based on detailed information on the flows of people, matter, and energy that take place in each city, including their interrelations.

BOX 7

Estimation of human damage due to hurricanes in Santiago de los Caballeros (Dominican Republic)

Problem

In the city of Santiago de los Caballeros, hurricanes and tropical storms are among the main risk sources, accounting for 18.75% of the historical events registered in the city, with a frequency of about 2 times a year. In a recent extreme event, the city was hit by the tropical storm Olga (December 12, 2007), which produced several deaths and material damage in dwellings, as well as street furniture and means of transportation.

Methodology

Human vulnerability to hurricanes and tropical storms results from the joint occurrence of floods and strong winds.

Floods

In the case of floods, population density is one of the key vulnerability factors, since it determines the number of people that could potentially be in a place reached by flood waters.

Three indicators of human damage due to floods have been obtained:

- Number of fatalities and seriously injured: The death probability depends on flood depth, velocity and water rise rate (Jonkman et al. 2008).
- Number of affected people: Those people censed in areas where the flood depth associated with a given event exceeds 0.3 meters.
- Number of people in need of shelter for an extended period of time: It is calculated based on the number of people censed in dwellings that collapse due to floods.

It has been assumed that in the whole area under study the rise rate of the water exceeds 0.5 meters per hour, which means an exposure coefficient of 1% for the people censed. This factor indicates that only a small portion of the population is exposed to risk conditions, with no access to high-lying places or some kind of shelter.

Winds

Unlike floods, which affect very specific areas in the urban space, winds have a spatial scope that covers the whole area under study, so the number of people that could suffer problems due to this phenomenon, and consequently a change in their daily life, is high, especially in a major hurricane.

Results

The results for human losses indicate that fatalities due to natural disasters in Santiago are not particularly high. The estimated deaths are not due to the collapse of buildings or infrastructure, but to the drowning of isolated people, probably elders, sick people or children.

As regards the number of affected people, figures are actually higher, since large rain events and riverine overflows cover – although with low depths – a large part of the urban area. Another interesting indicator is the number of people left homeless; in this case, said indicator shows relatively high values, indicating that in Santiago human risk in the event of large floods is higher than suggested by the fatality figures.

Besides, when it comes to the people that can potentially suffer damage from wind, it is observed that most of them live in the

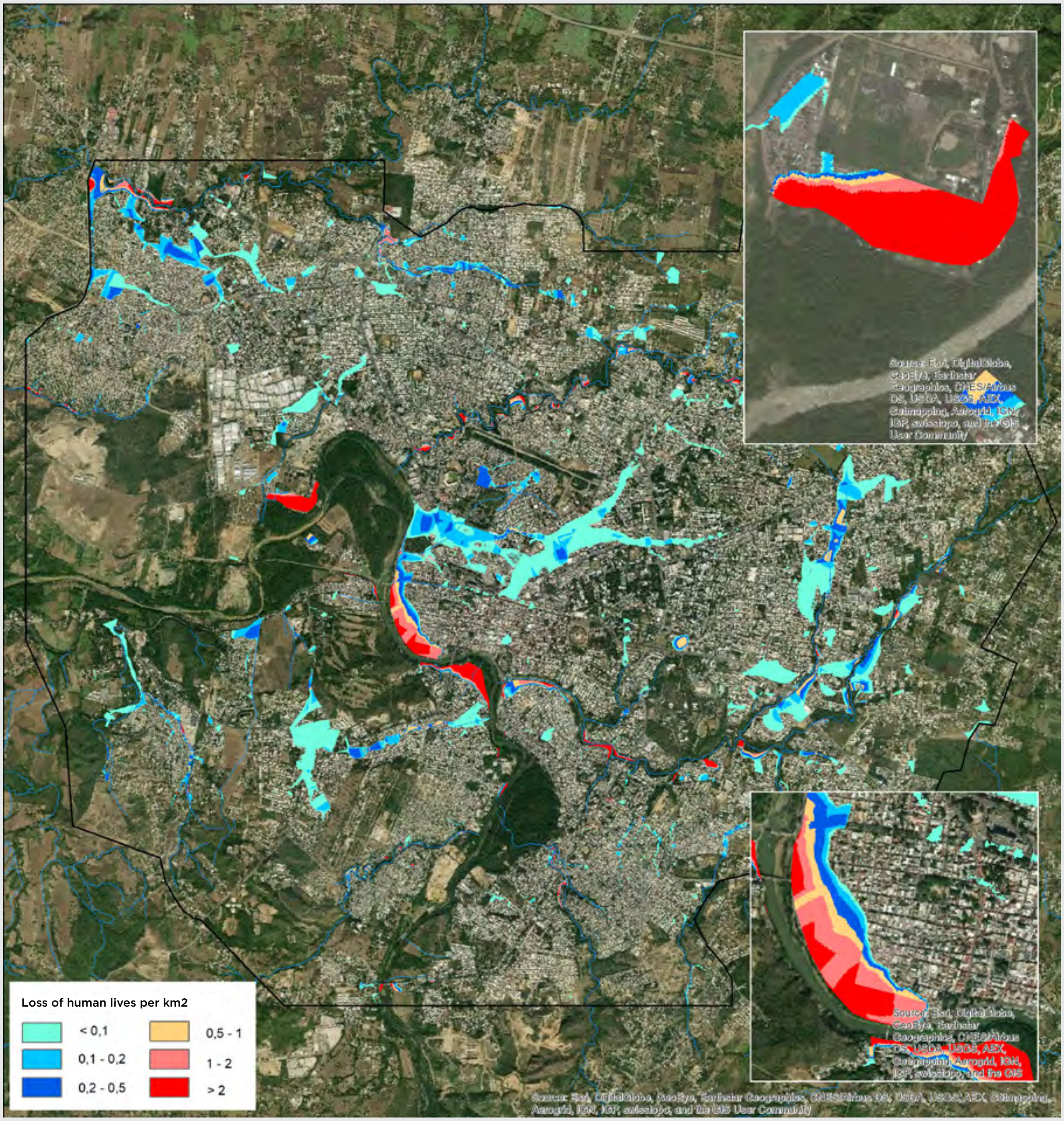


Figure 28 | Loss of human lives per km^2 T100 years.

most precarious dwellings, with roofs made of waste material and zinc sheets, whereas in the middle classes, the number of damaged people is very low, since the damage produced in buildings is low, even in extreme events.

BOX 8 ——

Incidence of diseases in the housing community located inside Los Patos lagoon in Cumana (Venezuela)

Problem

The “Laguna de los Patos” lagoon system, located in the city of Cumana and declared a Tourist Interest Area, Littoral Park, in December 1978 due to its great environmental importance (for being a regular transit point for several species of birds and crustaceans), currently hosts three informal settlements that are in irregular conditions: La Malagueña, El Chispero (La Lagunita), and La Encantada (marked with circles in Figure 29), that occupy approximately 3% of the area declared as park.

The continuous anthropic action over the system, which involves (i) dumping of urban solid waste and (ii) spilling of wastewater from adjacent urbanizations and from the city’s water treatment plant itself, which is currently not working, has caused problems in terms of water quality (most notably, episodes of strong eutrophication) and in the lagoon bed (accumulation of contaminated mud), which affects the health of the resident population.

On top of this, almost all the houses that are part of these communities dump their waste in septic tanks or directly to the environment and do not have waste collection services, so the waste is either dumped into the environment or burnt. Although families are poor and thus produce much less garbage than any urban community, not separating or treating the garbage negatively impacts the area.

Methodology

To determine the current condition of these communities, a census was conducted in order to diagnose their social, economic and environmental aspects, including an analysis of the health conditions of the population living in the littoral park.

Results

As a result of the census, in terms of health conditions it was found that 8% of the residents have some type of disability and 21% some disease. The disability percentage is similar to the one found at a national level, according to the last census of 2011, which revealed that around 6% of the Venezuelan population has some disability.

Disabilities include, most notably, blindness and absence of lower extremities.

As regards diseases, the presence of cancer in 36% of the sick people and the percentage of people with hypertension is noteworthy. La Malagueña has the highest number of sick people. In La Encantada, the number of people with respiratory illnesses is striking.

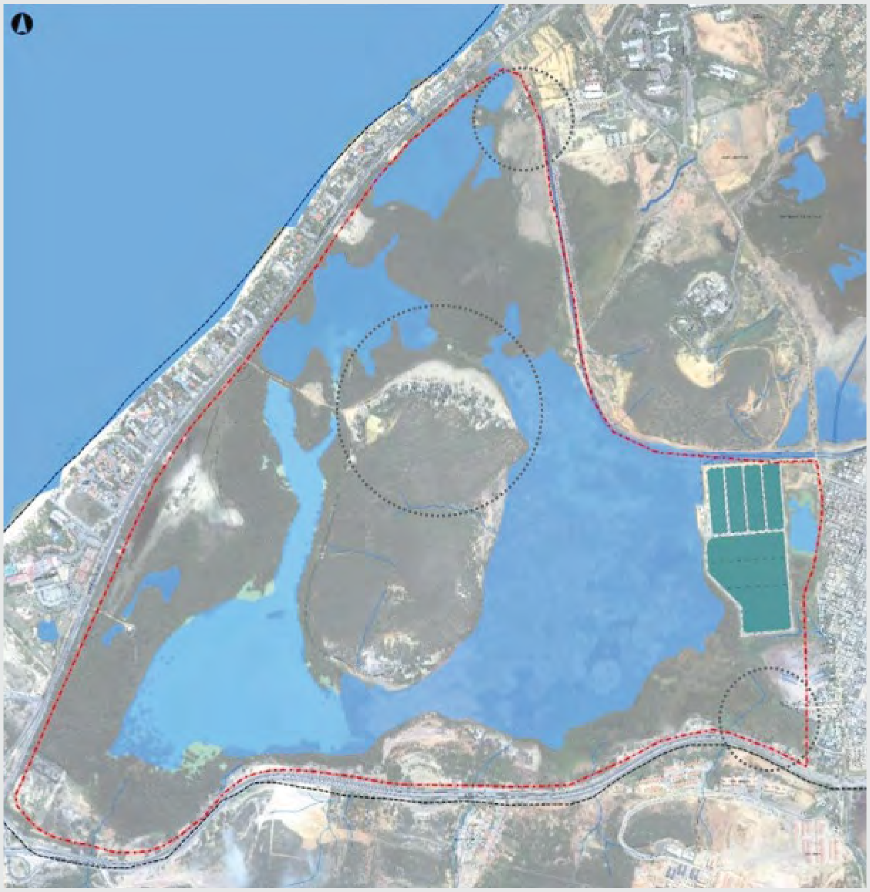


Figure 29 | Location of the communities in Laguna Los Patos.

LA LAGUNITA

1.2 hectares

2.3 dwellings

26 households

LA MALAGUEÑA

6.65 hectares

57 dwellings

63 households

191 people

LA ENCANTADA

2.1 hectares

65 dwellings
(12 with absent occupants)

56 households

214 people

	LA MALAGUEÑA		LA LAGUNITA		LA ENCANTADA		TOTAL	
TYPE OF DISABILITY	NUMBER OF PEOPLE	%	NUMBER OF PEOPLE	%	NUMBER OF PEOPLE	%	NUMBER OF PEOPLE	%
BLINDNESS	3	21.43	3	20%	0	0.00	6	19.35
INTELLECTUAL DISABILITY	1	7.14%	2	3.33%	0	0.00	3	9.68
NO LOWER EXTREMITIES	3	21.43	3	20%	0	0.00	6	19.35
NO UPPER EXTREMITIES	2	14.29%	2	13.33%	1	50.00	5	16.13
OTHER DISABILITIES	5	35.71%	5	33.33%	1	50.00	11	35.48
TOTAL	**14**	**100%**	**15**	**100%**	**2**	**100**	**31**	**100**

Table 9 | Communities in Laguna de Los Patos. Type of disability. Source: Census in La Malagueña, February 2017.

	LA MALAGUEÑA		LA LAGUNITA		LA ENCANTADA		TOTAL	
TYPE OF ILLNESS	NUMBER OF PEOPLE	%	NUMBER OF PEOPLE	%	NUMBER OF PEOPLE	%	NUMBER OF PEOPLE	%
Cancer	27	50.94	1	11.11	1	5.26	29	35.80
Epilepsy	1	1.89	1	11.11	0	0.00	2	2.47
Hypertension	12	22.64	0	0.00	0	0.00	12	14.81
Respiratory	5	9.43	3	33.33	15	78.95	23	28.40
Diabetes	1	1.89	4	44.44	3	15.79	8	9.88
Cardiac	5	9.43	0	0.00	0	0.00	5	6.17
Mental	2	3.77	0	0.00	0	0.00	2	2.47
TOTAL	**53**	**100**	**9**	**100**	**19**	**100**	**81**	**100**

Table 10 | Community of Laguna de Los Patos. Type of disease. SOURCE: Census in La Malagueña, February 2017.

3.6 Multi-risk analysis: the case of hurricanes

Section 2.5 addressed the calculation of the hazard associated with the passing of a hurricane as a characteristic example of a multi-risk analysis. Many alternatives were proposed, ranging from the simplest ones, based on expert judgment, to more computing-intensive ones, to solve a problem that is formally complex and requires a lot of information (not usually available) for it to be addressed exhaustively.

The determination of damage in a multi-risk environment adds a supplementary dimension of complexity to the one presented in the calculation of the hazard, and usually requires adopting hypotheses based on experience and a hefty dose of specific knowledge of the damage mechanisms associated with historical events in each place under study. Once the multivariate risk events have been characterized, it is confirmed that the damage derived from the application of the vulnerability functions described in previous sections cannot be added up by applying such functions individually and independently for each type of individual risk. For a hurricane that, for example, has associated winds of 200 km/h and water levels of 2m in a certain urban area, the damage resulting from both phenomena acting jointly is not the overlapping of the damage caused by wind and the damage caused by flooding derived from their specific vulnerability functions. In these cases, the most evident option is to build multivariate vulnerability functions, based on experience and the HAZUS and CAPRA databases. For hurricanes, it would be an expression that yields the percentage of the exposed value that is damaged in a certain type of dwelling, for any combination of water level and wind speed. This would satisfactorily solve the problem, but for the fact that such vulnerability functions are not available in the literature and must be formulated ad hoc by the technical experts involved.

A viable procedure to build multivariate functions (bivariate, in the example of a hurricane), which has been used with satisfactory results in certain cities of the ESCI, is to fully consider the damage associated with one of the involved phenomena (e.g., wind) and introduce a damage overlap factor (DOF) into the losses due to each of the other phenomena (in the example of a hurricane, the water level). Therefore, the total damage (TD) produced by a hurricane of wind intensity W and water levels H would be: TD = D(w) + (1-DOF) · D(H), where D(w) and D(H) are the individual damage from wind and water.

The DOF represents the intersection of the sets of components of a certain asset that are exposed to each hazard (for instance, following the classification proposed in section 3.3.) for each hazard level. The DOF will be zero if the damage produced by wind and that produced by water affect independent (structurally disconnected) elements, like when wind below 150km/h destroys the roof and some high windows of a house, while a simultaneous flood with elevations below 1m only affects the equipment and systems in the basements and first floor. There will be a certain wind speed and a certain water level at which the damage mechanisms of each phenomenon will start to compete for the same exposed elements – this is why the damage from individual hazards is not additive. It is at that point that the overlap factor becomes higher than zero, to reduce the damage from one of the phenomena and avoid double counting. There will ultimately be a certain wind speed that will destroy the whole of the assets (e.g.,

above 300 km/h for a good quality house), at which point the DOF will be equal to one (full overlap, zero water damage), since there will be nothing left to be destroyed by flood, regardless of its scale. It may be argued that this procedure turns the difficult task of finding a bivariate vulnerability function into a not less difficult task of finding the expression of the overlap factor – which is ultimately also an intermediate expression of this kind. However, the value of the DOF can be estimated by applying the set theory (intersection of the elements exposed to multiple hazards within one same asset), based on more detailed knowledge of the way in which the damage mechanisms operate, whereas the task of defining a vulnerability function of two inputs is more speculative.

This approach proposes a simple and logical method to build multivariate vulnerability functions based on the functions provided by CAPRA or HAZUS in order to make an estimation of the damage associated with multi-risk events. However, the actual problem is very complex and no simple procedure is capable of representing all the processes involved, whose thorough analysis is a subject matter of research and exceeds the scope of this document.

3.7 Calibration and validation of risk models

All models, including those previously described to quantify hydroclimatic risks, are a simplification of reality and include parameters that can be adjusted to each case under study through a calibration process. Besides, for some types of models it is necessary to ensure, through a supplementary validation process, that such calibration does not lead to inaccurate or even incoherent results in certain extreme conditions.

The calibration and validation of models requires data for the different calculation stages, and the quantity and quality of such data determine the work procedure and the results that can be expected. For methodological purposes, the models included in this document can be classified in three large categories:

1. **Hydroclimatic models:** these are the models used to obtain the calculation series for the variables representing the hazard sources, such as waves at undefined depths, rainfall, and peak flows. They also include the spatial statistics techniques used to spatially complete specific data. These are complex models with a global or regional calculation domain, and the most complex ones are operated by meteorological centers or specialized agencies.

2. **Hazard propagation models:** they are used to transform the hazard source variables into the variables that are significant for damage purposes, within the work area and, therefore, on a regional or local scale. This category includes hydrological models (transformation of rainfall into flows), hydraulic models (transformation of flows into water levels), wave propagation models (transformation of open-sea waves into coast waves), coastline evolution models, etc.

3. **Socioeconomic models:** they are used to combine a hazard with vulnerability factors to determine risks. Based on the approach used in this document, these are simple models, based on the characterization of certain dimensionless functions and assets or people at risk, to which such functions are applied.

Potentially, in a city there will be data to calibrate the three types of models used, starting from the climatic sources of a hazard, following with the propagation models and ending with the socioeconomic models. *Table 11* summarizes the most common input data and adjustment parameters of each stage.

From a strictly practical perspective, the calibration process in urban risk calculations within the framework of the ESCI studies can be simplified in three essential steps:

1. Select known historical disasters of different scales (if possible, no less than two: one with a return period of less than 10 years, and another one of a more extraordinary nature) and, based on documentary sources, establish the basic parameters that characterize them, such as the scale reached by the hazard variables (rainfall, levels, flows, wind speed, coastal retreat, etc.) and the scale of the damage suffered, in both economic and human terms.

2. Calibrate the hazard models (hydroclimatic and propagation models) for those events so that they meet the observed conditions.

The asymptotic behavior of the extremes adjustment of the hazard source variables is particularly important because they directly transfer their damage probability of occurrence.

3. Calibrate the socioeconomic models in order to obtain damage parameters that are similar to those observed. Although, the information available is usually not sufficiently disaggregated to make an ad hoc calibration of the dimensionless damage functions, it is certainly possible to refine the value of the assets at risk by category.

Most of the models do not necessarily require a validation procedure, either because they are models of processes where the parameters have a physical meaning and predefined default values, or because they are simple procedures (like damage functions) with limited results. However, it is recommended carrying out a combined calibration-validation procedure when using heuristic-conceptual models (e.g., based on the theory of systems), purely statistical models, or models that have not been validated by the scientific-technical community.

	DATA	PARAMETERS
HYDROCLIMATIC MODELS	**Instrument series of rainfall and flows. Series of open-sea waves. Series of sea level.**	• Parameters of climatic downscaling models. • Parameters of adjusted distributions of extremes. • Hydrological parameters on a large scale.
HAZARD PROPAGATION MODELS	**Water levels reached in different points of the area under study.** **Maximum retreat of the coastline in specific sectors.**	• Flow roughness factors (Manning, Chezy, or similar). • Local hydrological parameters (SCS-CN, time to peak). • Waves propagation parameters.
SOCIOECONOMIC MODELS	**Estimation of the economic damage in historical disasters.** **Number of deaths and refugees in historical disasters.**	• Damage functions form parameters. • Econometric parameters (dwelling stock, unit prices, etc.). • Human exposure parameters.

Table 11 | Summary of the most common data and calibration parameters in risk calculations.

3.8 Uncertainty in risk calculations

As a supplementary activity related to the calibration and validation process, there is the analysis of uncertainty, which in this context means the estimation of the confidence levels of risk results, considering them not as unique values, but as random variables with their probability function. In order to calculate each of the described risk indicators, we have introduced a number of methodological steps carrying different sources of error which add successive uncertainty layers to the results:

- **Uncertainty in the hazard sources:** it exists in both the gross instrument data and the models used to determine the dominant variables that are used as input to the models of processes (the hydroclimatic models in the preceding section). For rainfall, for example, there are at least the following uncertainty sources: 1) the instrument error associated with data from rain gauges provided by meteorological agencies or organizations; 2) the error in the spatial interpolation of those data points to extend them to the field of the catchment areas under study; and 3) the error from adjusting a distribution of extremes to obtain the maximum rainfall with different return period. A noteworthy source of uncertainty is that associated with a hazard in future scenarios, where it is necessary to incorporate the potential effect of climate change according to the different greenhouse gas emission pathways.
- **Uncertainty in the propagation of a hazard:** the source variable of a hazard must be transformed into variables that are representative for purposes of the selected damage mechanisms (for floods, the depths and maximum velocities field). The hazard propagation models (hydrological, hydraulic, wind, morphologic evolution, among other models) used for such purpose include execution parameters whose values carry a degree of uncertainty that propagates – often non-linearly – to the results; if a calibration and validation process has been carried out, then the uncertainty will be lower, but will always be present. Besides, it is not possible to accurately predict the behavior (geotechnical, structural and hydraulic) of the infrastructures that transform the hazard, such as bridges, breakwaters, canals, etc. The moment their probability of failure – possibly associated with multiple mechanisms – is considered, a new source of uncertainty arises.
- **Uncertainty in the exposure and vulnerability:** the spatiotemporal distribution (for mobile receptors like people, vehicles, animals, etc.) of the elements capable of being damaged and the behavior patterns of the potentially affected living beings cannot be specified. It is also not possible to accurately predict the features that determine the vulnerability towards a certain damage mechanism (e.g., the age structure of the affected population, or the total value of the assets at risk).
- **Uncertainty in the damage functions:** the dimensionless relationships between a hazard and the proportion of damage cannot be established for certain due to not knowing the specific features of each building or person and other random factors. Damage functions are useful empirical instruments, but should be applied with their uncertainty levels, rather than as simple biunivocal relationships between a hazard and its effect.

In most studies addressing the risks that affect cities, including the ESCI, the uncertainty is disregarded and only the mean values of the key variables are propagated along the risk calculation process (pseudo probabilistic approach, according to IDB accepted terminology). A valid and relatively simple procedure to quantify uncertainty, which has been frequently used in studies addressing seismic risks (Molina, Lang, and Lindholm 2010) and the risk of tsunamis (Annaka et al. 2007), is the use of logic trees. Basically, this procedure involves considering for each sub-process in the risk calculation chain several possible events, with their associated probability; this entails converting the continuous density functions of the calculation variables that are considered most relevant into discrete functions. Figure 30 shows a-simple logic tree (four levels with three alternatives each) to determine economic losses due to riverine floods in a city, incorporating uncertainty; the tree must be re-calculated for each return period considered. In this case, it is necessary to run the complete sequence of models 81 (3^4) times in order to rebuild the damage density function for this return period as a discrete function. This function is used to obtain confidence levels.

This probabilistic approach to risk requires significantly increasing the number of times the sequence is run as compared to the pseudo-probabilistic procedure, so for practical reasons it is only viable if two requirements are met: 1) the whole calculation sequence, with the models fully connected, is automated, and 2) the sequence is computationally robust and has a reasonable running time. Given that many bi-dimensional hydraulic models used to calculate flood risks (and possibly other models) are third-party packages that do not meet these conditions, this procedure and others that are similar are not widely used. Even so, studies using advanced probabilistic techniques are becoming more and more common in the academic field, whose purposes and limitations are different from those in the field of consulting.

A soft version of the uncertainty analysis, which should not be disregarded when a fully probabilistic analysis cannot be conducted, is a sensitivity analysis. In this case, the technical staff in charge of the analysis select, based on expert judgment, some variables of the calculation process and enquire about their influence on the results. The sensitivity analysis, in its most accessible version, provides an answer to questions like:

- How much do the design flows in a river stretch change if the values of the curve number (CN) adopted for the catchment area change?
- How much do water depths change in a floodable area if the flow roughness coefficients change within a range of plausible values?

It is recommended that all hydroclimatic risk studies include a section with a basic sensitivity analysis that quantifies the dependence of the final results on the values adopted for certain key parameters.

The calculation of uncertainty, following the above-mentioned procedures or others, requires data to characterize the differences (residue) between the estimations and reality. However, in studies addressing the risks that affect cities such data are not always available, so the problem must be solved by extrapolating the uncertainty measured in other case studies. Due to all of the above mentioned circumstances, uncertainty analyses tend to produce very broad confidence thresholds for the output variables, which may turn uncertainty into an awkward truth for the teams responsible for preparing the studies (due to the greater demand of data that are not usually available, and the greater complexity of the calculations required), as well as for the receptor entities, which perceive greater vagueness in the results and, consequently, in the conclusions that can be derived from those results. When incorporating uncertainty in risk studies, it is common for practitioners to perceive few incentives, since they must assume an increase in the time of execution and budget for the works (which also require more qualified staff), in order to get a product that is more difficult to construe, communicate and, ultimately, defend as a basis for certain possible actions. Within the framework of a technocratic paradigm, the binomial formed by technologists and risk managers tends to preserve the accuracy aura that society attributes to science and, by extension, to related – but not strictly scientific – disciplines, such risk analysis. Ultimately, the uncertainty issue emerges as the "elephant in the room" in risk studies, and everything points at the fact that, on awaking, the animal will still be there[2].

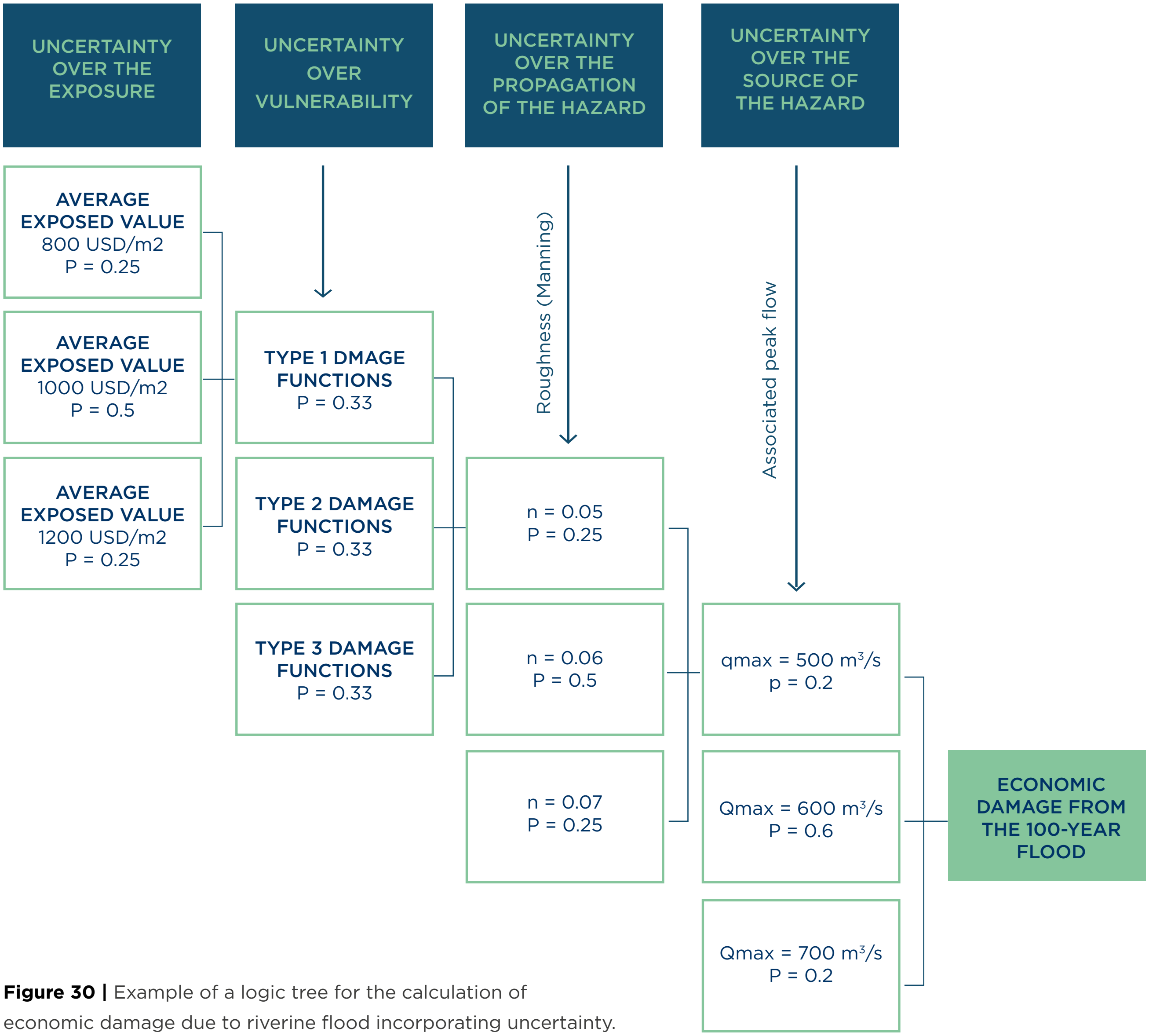


Figure 30 | Example of a logic tree for the calculation of economic damage due to riverine flood incorporating uncertainty.

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[2] *In this context, those responsible for conducting risk studies become unusual protagonists in the famous micro-story by Augusto Monterroso.*

4

Urban drought risk —

4

Unlike floods, water resource shortage in urban environments is a risk that materializes progressively and whose critical periods last for weeks or months. In addition, the damage it causes is indirect, without there being a destruction of physical assets or human losses. Due to these and other reasons, urban drought risks cannot be analyzed through procedures like those presented in previous chapters.

This section will focus on defining a general methodology and providing calculation criteria for urban water scarcity risks, including the supply of water for human consumption, water for commercial and industrial uses related to a city and, finally, water for street cleaning, irrigation, and other secondary activities. This document does not address agricultural drought or droughts that would affect large industrial users or the energy sector.

4.1 Water balance quantification

The general framework to evaluate the urban drought hazard is a water balance obtained as the difference between the available resources and the necessary resources, considering the city as a spatial work unit. Such balance should be dynamically considered over time, preferably using a monthly or quarterly scale, which will ultimately generate a series of values (positive in the case of an excess and negative if there is a deficit) during a sufficiently long period (if possible, 20 to 30 years at least). Based on a series of these characteristics, it is possible to derive the supply guarantee (percentage of time when demand is fully supplied), which can be global or by month of the year, and make a diagnosis of the situation. There follows a description of basic aspects and methodologies to estimate available resources and demands; reference is made to some factors that complicate what may seem a simple issue at first glance.

Estimation of the available resources.

The water available at its origin, or available gross resources, is obtained by adding up the following sources:

1. **Surface waters flowing from rivers, streams and springs**

The amount of gross available water is determined by the smallest of two values: the extraction capacity (possibly including the capacity to treat it and feed it to the network) and the available run of river flow. The latter is in turn determined as the difference between the total run of river flow (derived from hydrological modeling under a natural regime) and flows committed to non-supply uses (concessions downstream and ecosystem maintenance flows, especially).

2. Surface waters from lakes, dams and glaciers.

In the case of lakes and reservoirs, the available gross flow is the result of certain management criteria, affected by the hydrological capacity and operation of stocks, and obviously limited by the hydraulic capacity of the elements used for extraction and treatment. This leads to one of the first difficulties faced when estimating the resources that are available to a city: they depend on the regulations applicable to the exploitation of the lakes and reservoirs that are linked to the network and, therefore, vary depending on the degree of optimization of such regulations. Glaciers represent a unique source of water resources, which is very important in some Andean areas (Box 9 includes an example of resource evaluation, including resources originated from glaciers in the city of Huancayo, Peru).

3. Underground waters.

The available gross water from an aquifer depends again on the capacity of extraction pumps and of the aquifer. While less evident, an aquifer works as an underground reservoir (with a capacity and inflows/outflows that are more difficult to evaluate), so the resources available are also affected by the exploitation criteria adopted.

4. Water from desalinating or reuse plants.

This is the simplest case to evaluate in terms of available gross resources, since they depend on the installed capacity of the relevant plant(s). It is obviously possible to modulate water production according to exploitation criteria, but, contrary to the case of reservoirs and aquifers, present decisions do not alter future operating restrictions.

The available gross resources ultimately depend on the number of water masses linked to the supply network, on the geometric and hydrological characteristics of those water masses, on the capacity of the technological systems used to extract water and, finally, though not less important, on the criteria adopted to exploit the regulated resources (reservoirs, lakes and aquifers). From an operational perspective, it is the latter management aspect that brings the greatest complexity to the calculation of available gross resources, since it adds a system memory factor and requires using time series models, while flowing resources or resources from industrial premises can be calculated for each time increment autonomously and independently.

Available net resources is the total volume of water that is available for consumers as measured in the points of consumption, rather than in the extraction points, for each period of time. The available net resources result from applying the following changes to the aforementioned gross resources:

1. Physical losses of water in the network adduction, treatment and distribution processes.

They usually entail a decline in gross resources. However, it is convenient to differentiate the physical losses from piping leaks and breakages, which represent water that is not used by anybody, from the illegal connections to the distribution network, which, albeit reducing water availability in the official points of demand, do supply consumptive uses of part of the population – with greater or lesser efficiency.

2. Alternative resources: community or private wells and sources, rainwater storage systems, delivery with water trucks, use of bottled water, etc.

These resources represent and increase, usually small and with a high relative cost (though it is sometimes subsidized), in the available net resources channeled through the distribution network. They are, however, the only solution in urban areas not served by the utility network, where a non-negligible proportion of the urban population is settled in many cities of Latin America and the Caribbean. Due to the systems based on alternative resources being usually deregulated and operating on a small-scale, they are hardly efficient and are exposed to quality issues (except for the use of bottled water, which has other disadvantages like being very costly and presenting environmental externalities).

CALCULATION CONSIDERATIONS

The assumable losses in a supply network, below which marginal maintenance costs start to equal the marginal saving, depend on multiple factors: network topology and length, average pressure, resource availability, etc. As a general rule, most cities should aim at having a percentage of non-revenue water below 20% of the gross processed flow. Usually, once loss reduction mechanisms are effectively activated, it is possible to reach values that are close to 10%.

Demand estimation

As already pointed out, urban water demands can, for operating purposes, be sub-divided in different categories:

- Domestic uses, including the hotel industry.
- Commercial and office uses.
- Industrial uses.
- Other uses (street cleaning, irrigation, etc.).

Estimating domestic demands is one of the most controversial tasks in evaluating the urban drought hazard. Per-capita per-day water requirements in a given city depend on multiple factors including:

- Standard of living or income level of the population.
- Weather (temperatures, precipitations, and average humidity).
- Dominant building typologies and city model.
- Cultural and educational level. Social capital.
- Perceive service quality (supply cuts, water quality, service pressure, etc.).
- Water price and tariff structure.

In the analysis of a specific city, the actual water duties registered over a number of years can be established by dividing the served resources (or, as a proxy, those invoiced) by the total population (fixed and floating). It is also useful to collect information on water duties in cities with similar characteristics, especially in the same weather context and with the same level of socioeconomic development.

Given that risk assessments attempt to make a future projection of their results, it is necessary to forecast demands by applying the scenario concept and defining at least two scenarios (although three or four may be better): a trend scenario contemplating that the evolution rates observed in the past years will be maintained, and a smart scenario that results from considering an intensification of the measures aimed at reducing consumption. Note that the smart scenario - in terms of consumption reduction - is not necessarily equivalent to a developmental scenario in terms of an improvement in the standard of living since an increase in the per-capita income, often related to an increase in water supply, may be coupled with a decreased efficiency in water use.

Once the current and future water duties have been defined, to determine domestic demands it is necessary to establish both the existing population (floating and fixed) and the projected population for the period of time considered. Another controversial issue arises at this point, although contrary to the calculation of water duties, the decision on the foreseen demographic evolution should not be the responsibility of the technical specialists in charge of assessing risks, but of other external agencies (urbanism, tourism, housing department, etc.).

The estimation of the rest of uses, like commercial and industrial, may likewise be addressed by allocating water duties, which, in these cases, are expressed in units that are different from those used for domestic consumption:

- **Commercial uses:** average water requirement by hectare and day in a commercial area with certain characteristics.
- **Industrial uses:** for large industries, it is necessary to consider the actual consumption based on historical data and projections. For industrial zones or areas with multiple diversified companies, again, it is possible to establish water allocations by unit area (m^3/ha·day) based on the prevailing industry type.
- **Other uses:** for municipal uses like street cleaning or irrigation, a water requirement must be established by urban area unit.

Urban water balance

The water balance results from subtracting from the net available inputs the estimated demands, both in current conditions and for the considered future scenario projections. If long monthly series of inputs and demands are available - as recommended -, the result of the water balance is a time series of the same length from which the following urban drought hazard indicators can be obtained, among other data:

- The mean supply guarantee, defined as the percentage of time when the balance series is equal to or higher than zero.
- The supply guarantees by month or by season.
- The mean volume of the annual deficit and of the deficit by month or season.
- The annual deficit extreme regime (e.g., deficit exceeded once every 10-20 years).
- The frequency (number/year) and mean duration (usually months) of deficit series.

CALCULATION CONSIDERATIONS

While for practical purposes it is advisable to separate the estimation of water supply and water demand, demands in a city depend on the supply conditions: service continuity, average pressure, quality of the water supplied, tariff structure, etc. Any of these factors may lead to both positive and negative anomalies in the registered consumption patterns, which tend to disappear as the underlying causes are solved.

BOX 9 ——

Implications of climate change for urban drought risk. the case of Huancayo (Peru)

Problem

Urban drought is one of the most important factors that limit development in the city of Huancayo. Surface water sources are exploited to their limit during the low-water period and the hydrological deficit is partly compensated for with the additional input of underground water sources that supply low-quality costly water. This situation has reached a critical point over the past few years, resulting in relatively frequent and long interruptions of water supply.

The main causes are the following:

- Decrease in the resource available on the surface due to water shortage in the Haytapallana peak as a result of climate change.
- Competing uses - apart from urban water supply, the surface resource is used for other purposes, especially agriculture.
- Increased demand as a result of an exponential population growth in the past few years.

Methodology

The effect of climate change has been incorporated to the study of urban drought risks through the changes it generates in the available resource (inputs) in a fully probabilistic way. In this case, the main input source is the Shullcas river, so the alterations in the available resource depend on the future climate evolution and on the land uses in that watershed.

To quantify the available resource, a hydrological model that uses a monthly scale has been built. Based on a series of precipitation and evapotranspiration data, the model determines the flowing flows in the watershed. It has been necessary to build the model because the Shullcas river has the peculiarity of having a glacier at its head (Huaytapallana peak), which contribute an unknown portion of the total runoff water, which needs to be quantified. Therefore, a predominantly practical approach comprising the following steps has been adopted:

- Calibrating a conventional aggregate hydrological model using the neighboring watersheds, where the presence of glaciers is zero or negligible, in order to correctly reproduce rainfall inputs.
- Proposing an empirical model to simulate the glacier input adjusted based on data obtained from the literature, which includes a prognosis of the evolution of the glacial area (*Figure 31*).
- Creating a hydrological model as a combination of the conventional model and the module of aggregate evolution of the watershed head glaciers. This combined model has been validated with hydro-meteorological data available for the watershed and is used to generate synthetic series of inputs for the different climate change scenarios.

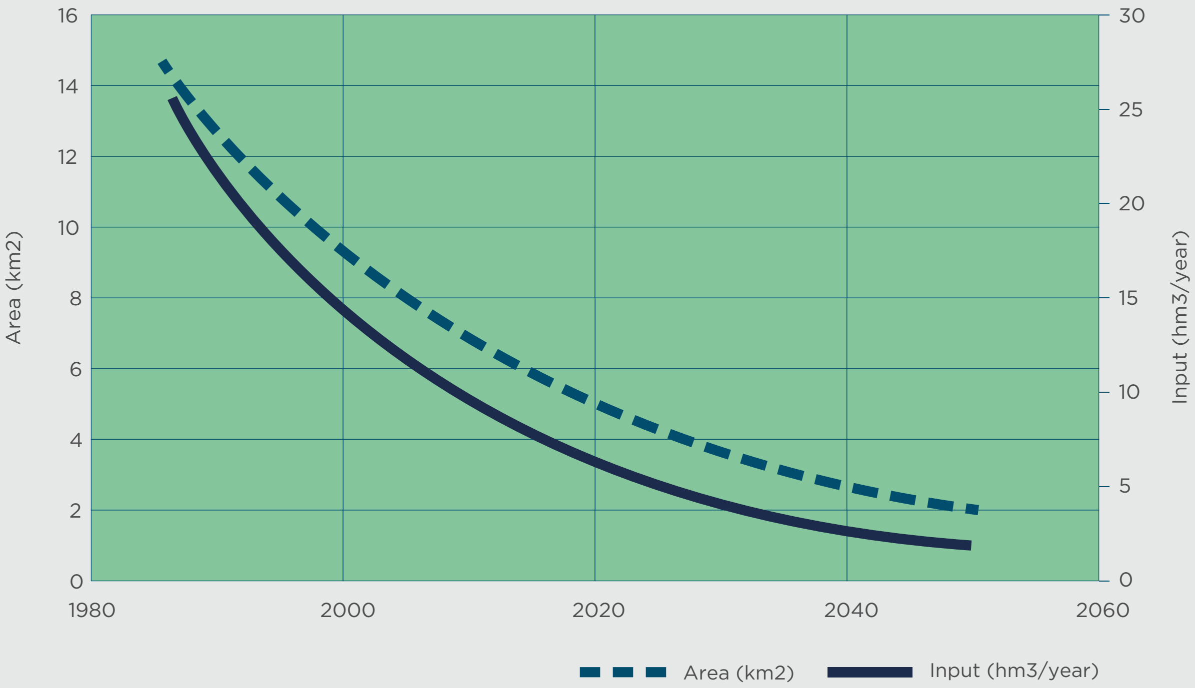


Figure 31 | Evolution of the glacier area and the mean inputs of the Huaytapallana peak in the Shullcas watershed, according to the proposed model.

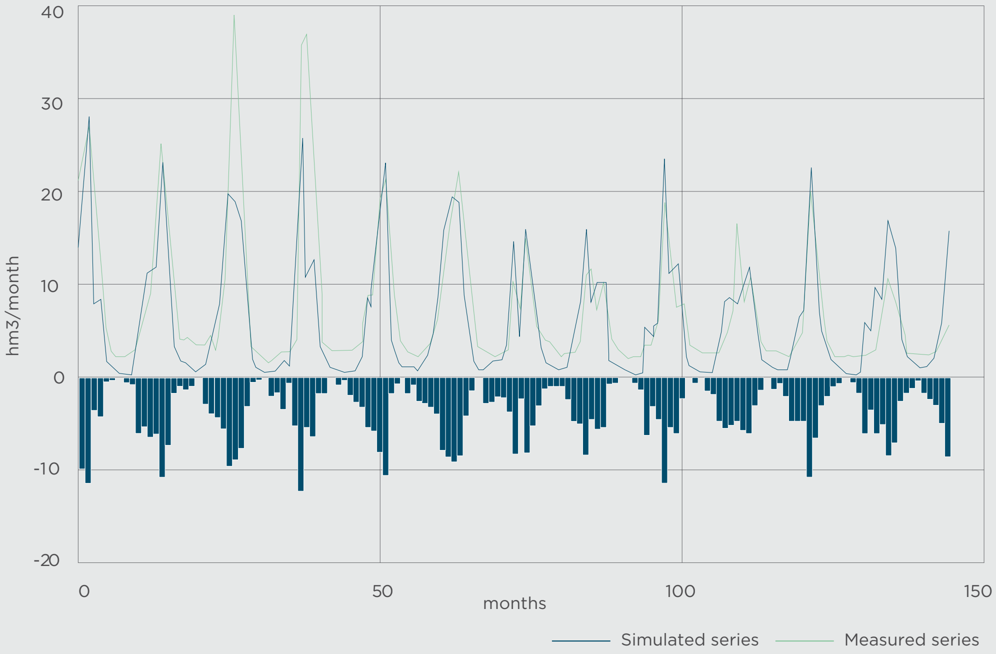
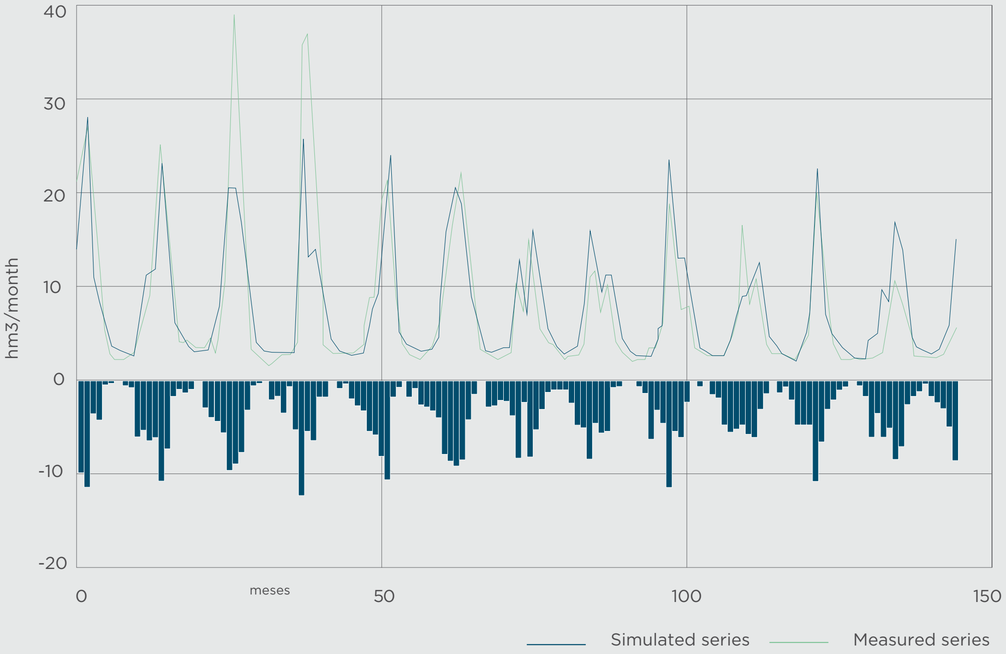


Figure 32 | Series of mean and simulated inputs during the calibration period. (Above) Conventional model, only considering rainwater inputs. (Below) Combined model of rainwater-glacier inputs.

As depicted in Figure 32 (Above), representing the rainwater input of the watershed, while the peak flows are properly adjusted, this is not the case for the base flow, while in Figure 32 (below), which includes the glacier input, the adjustment is good for both peak flows and low flows (except in two wet years).

Once validated, the model has been used to generate synthetic 30-year input series for the different scenarios (current, 2030, and 2050) based on potential precipitation and evapotranspiration series of the same duration.



- **Precipitation:** Rainfall series taken from the NEX-GDDP database available from the NASA Center for Climate Simulation for RCP 4.5 for the period 2006-2100 have been used.
- **Potential evapotranspiration:** The data used to calibrate the model have been taken and modified according to RCP 4.5 climate change projections for the average temperature regime, which are the result of global climate model simulations, collected under the Coupled Model Intercomparison Project Phase 5 (CMIO5; Taylor, Stouffer, y Meehl 2012).

RCP 4.5 CC SCENARIO		
TIME HORIZON	2030	2050
PRECIPITATION VARIATION	+3%	-3%
TEMPERATURE RISE	0.5-1°C	1.5-2°C

Table 12 | RCP 4.5 Climate Change Scenarios (2030 and 2050).

Results

Table 13 and *Figure 33* show the precipitations and inputs obtained:

As seen in the above table, while for the 2030 horizon year both the yearly average precipitation and the yearly average input show a slight increase as compared with the current period, this is not the case for the 2050 horizon, where there is a decline relative to the current conditions.

It is evident that the current situation in Huancayo is critical in terms of urban water supply and there is competition with agricultural water demand during the low-water period. In the future, the situation will be more critical due to the progressive melting of the glaciers located at the river head as a result of climate change.

The future urban water supply deficit cannot be exclusively solved by implementing demand-side management measures (voluntary cuts in consumption), reducing network losses, or improving the regulation for existing ponds, and it will be necessary to make large investments and deep changes in the management of assets.

SCENARIO	CURRENT	FUTURE	
TIME HORIZON	2015	2030	2050
SIMULATED PERIOD	2006-2036	2015-2045	2035-2065
AVERAGE PRECIPITATION [MM/YEAR]	861.63	893.36	835.89
AVERAGE INPUT [HM3/YEAR]	99.25	99.66	86.42
RUNOFF COEFFICIENT	0.59	0.61	0.56

Table 13 | Summarized results of inputs for the different scenarios.

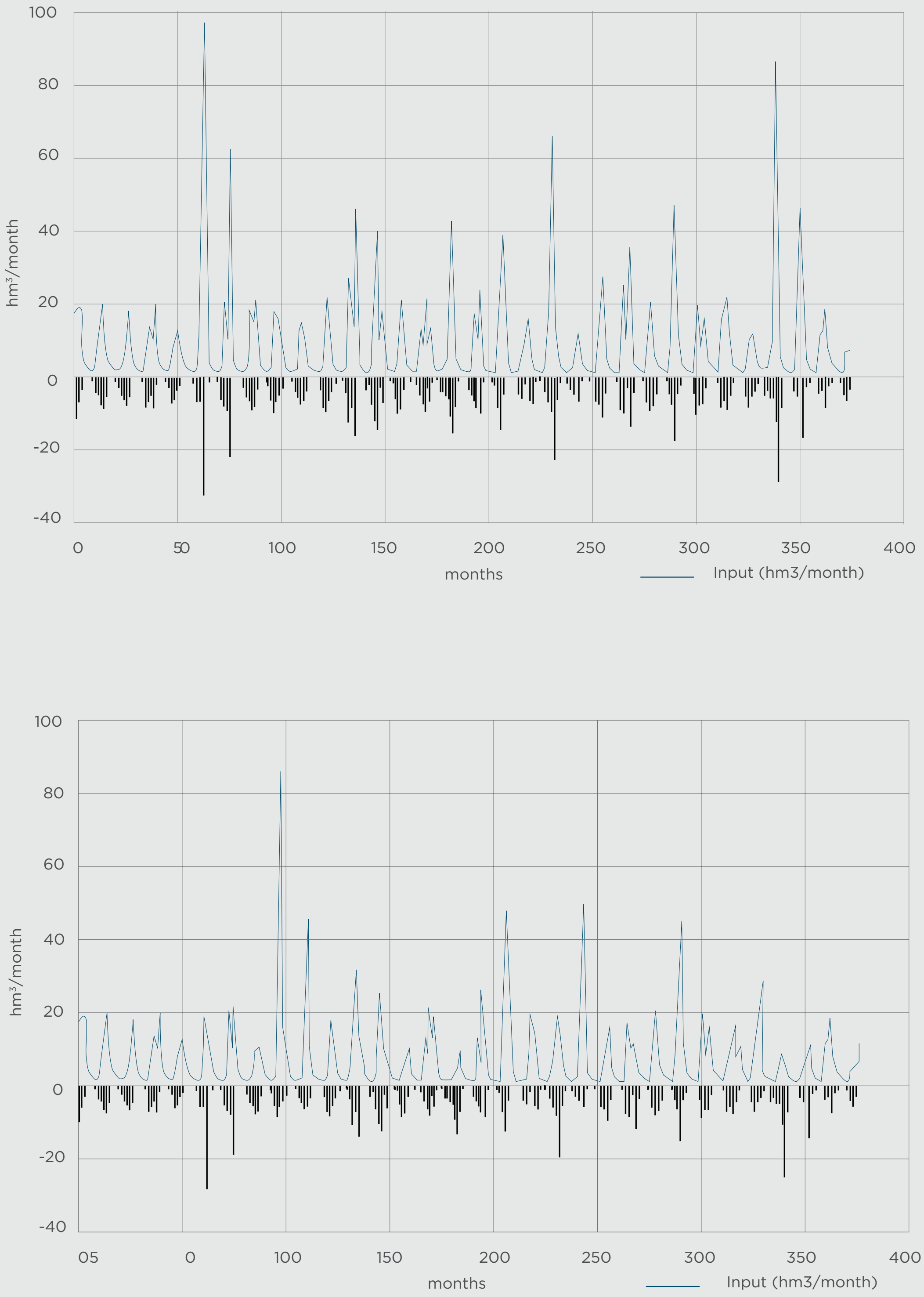


Figure 33 | Input series obtained for the Shullcas river watershed. 2030 (above) and 2050 (below) horizon years.

4.2 The effect of climate change on urban drought

Contrary to what has been described in the section on rapid-onset risks (2.6), climate change alters the availability of water resources in cities by altering the average precipitation, temperature and river flow regimes, that is, due to changes in the magnitude (mean value and standard deviation) of the hydroclimatic variables on a watershed scale, which is usually far larger than the urban patch. The increase in the spatial and time scales of the information required makes climate change estimations more reliable for assessing urban drought risks than for assessing risks from extreme events - at least at first glance. The generic calculation procedure used to establish available future inputs may be summarized in the following steps:

1. Establishing the influence area of the city in terms of resource availability, including all future sources of resources, not only those existing at present.

2. Collecting and analyzing the existing climate change information on a regional scale for the influence area. If there is not enough information or if the information available has not been sufficiently updated based on the IPCC results, it is recommended downscaling the general circulation models. The downscaling can be dynamic (mesoscale models) or statistical. This activity generally includes a calibration of results with instrument series of available meteorological data.

3. Characterizing future climate, for purposes of the relevant variables, for a target time horizon of usually 30 or 50 years (note that for statistical reasons, it is not correct to talk about climate change for shorter horizons). To estimate water resources, the most important variables are precipitations and temperatures, from which the mean evapotranspiration can be derived. This characterization may be directly based on the use of the synthetic series - on an aggregated scale of several days - just as generated by climatic models, or otherwise, where possible, a correction factor by month may be introduced for rainfall and temperature. The latter simplified procedure, based on disturbing the historical series with a factor for each month of the year, must be implemented provided that it is confirmed that it is statistically valid.

4. Applying the necessary process models to obtain series of the derived variables that are relevant, based on the previous series. This usually implies running the hydrological and resource management models again (see section 4.1).

The hypothesis that the magnitude of climate change is such that no significant alterations are produced in the vegetation types and cover and that the rainfall-river flow conversion processes remain roughly stable is implicit in the last of the previous steps. However, in certain regions, climate change may produce qualitative alterations in the watersheds (e.g., a forest transformed in shrubland or savanna), which will affect the water cycle beyond a change in precipitations and temperatures. The participation of ecology experts is required to evaluate these phenomena in each particular case, whenever there are signs that they may occur.

Finally, climate change may impact water demands due to temperature variations that may produce alterations – usually of the same sign – in the population's consumption patterns. While it is quite logical to assume that temperature increase will be coupled with an increase in water duties, it is also true that there are natural or imposed mechanisms to value and better manage water resources in a context of a warmer climate. Overall, water requirements, beyond a certain threshold that may be set at around 100 liters per person per day, do not depend so much on the climate but on other factors like the socioeconomic development level, the prevailing citizenship culture, and management effectiveness.

Climate change alters the availability of water resources in cities by altering the average precipitation, temperature and river flow regimes, that is, due to changes in the magnitude (mean value and standard deviation) of the hydroclimatic variables on a watershed scale, which is usually far larger than the urban patch.

4.3 Considerations on vulnerability and damage from urban drought

Among the risks that may affect a city, urban drought is a singular one because it manifests slowly and does not generate direct economic losses or human damage in its most visible forms (deaths and refugees). However, the indirect damage from an occasional or sustained lack of raw water in a city may be very significant, to the point that it may adversely affect socioeconomic development and end up limiting demographic growth and social wellbeing.

The conceptual framework presented in previous chapters to address vulnerability and, ultimately, damage is not fully appropriate to address the urban drought risk due to its effects on the socioeconomic system being complex, diffuse and time-deferred. There are, therefore, no commonly accepted calculation procedures or damage functions for urban drought. The most common symptoms through which urban drought manifests, ranked in decreasing order of negative impact, are the following:

1. Lack of access to the network.

Due to a lack of infrastructure, usually related to the potential users' inability to pay (which creates a context of uncertainty for potential investors), in many cities there are areas that are not connected to the water supply network. This is usually coupled with informal water markets, deregulated private wells, illegal connections to piping networks, subsidized supply through water trucks and public tanks, etc. These mechanisms usually guarantee basic subsistence conditions, but hinder any option of socioeconomic development and generate significant cost overruns for families. The most straightforward indicator of this problem is the percentage of the total population that is not connected to a supply network.

2. Seasonal supply restrictions.

When there is no sufficient water to supply all of the population's uses over certain periods of the year (usually during the dry season), supply restrictions that may last for several months, depending on the severity of the drought, occur. This leads to a decline in families' standard of living and limited economic activities, especially for the small businesses, which cannot afford paying higher rates or building their own infrastructures. On the other hand, due to the fact that this is a temporary phenomenon, those affected are aware of this problem and may anticipate it. In this case, the indicator of this problem is the mean water requirement available during the dry period (or yearly, if there is no such dry period), measured in liters per person per day. If the minimum requirement is not met, families may foreseeably be forced to get water from other sources (e.g., cisterns) subject to a significant surcharge.

3. Random supply restrictions.

Due to the poor condition of the water supply network (leaks, cracks, clogged pipes or pipes with an excessively narrow section, etc.), in many cities users experience water supply interruptions, pressure losses, and the supply of turbid water, on a regular but random basis – irrespective of the availability of raw water. To quantify this problem, it is necessary to estimate the mean supply guarantee, understood as the percentage of time that the service is rendered to an acceptable standard, in terms of both quantity and quality of the water supplied. Acceptability comprises certain quality standards for the service: maximum number of supply interruptions per year, mean service pressure, percentage of losses in the network,

5

Risk causes, mechanisms and indicators —

5

In the previous sections of this document we have presented structured quantitative procedures to determine the risks associated with certain natural events in urban settings.

Such calculation methods are based on the hypothesis that the future evolution of hazard and vulnerability factors – i.e. the two risk components – is essentially produced in a decoupled manner. Thus, a certain number of future climate scenarios that govern a hazard are combined with several urban development scenarios, which are usually projections of historical trends (trend scenarios) or idealized designs (smart scenarios), and future damage predictions are obtained from their possible combinations.

The first part of this manual (chapters 1 to 4) has mainly relied on the technocratic paradigm. In this second part, focused on defining risk reduction measures, the aim is to provide a holistic vision of risk, understood as a reality that is created and destroyed through historical processes – which are often complex – with different spatial and time scales.

5.1 Risk as a threat and as an opportunity

Although the ultimate objective of this methodology is to define risk reduction measures, it is convenient to first introduce a conceptual framework that helps understand humans' basic relations with their environment and, ultimately, the origin of risks. This initial discussion will attempt to present risk reduction measures not as technological prescriptions or remedies, but as interventions that, deliberately or not, operate on the multiple dimensions (physical, economic, legal, institutional, cultural, etc.) of a system whose evolution patterns we want to modify.

The primary objective is to answer a question that may be stated very simply, which is even obvious at first glance: what has led people who are at risk to be in such position? To answer this question, a dual model based on two sub-models or overlapping planes operating in a complementary and non-exclusive way is proposed. The two planes reflect the two faces of risk – as a limitation and as an opportunity for development – which are ultimately two ways of facing reality. On the one hand, the altered equilibrium model presents people as passive entities that endure or experience risks; from this viewpoint, risk is a supervening circumstance, an imposed reality. On the other hand, the rational subject model is, as its name suggests, based on the capacity of human beings to 1) analyze information, and 2) decide on their destiny, based on the result of such analysis. In this alternative perspective, people choose certain risks because, based on their subjective judgment, they appear to be the best relative option they have at hand to lead their lives.

While the first model tends to be given more prominence, with the rational subject model being considered an exception or anomaly, both models are appropriate to explain certain risk generation processes. With the prevailing perspective of engineering and natural sciences, it is hardly relevant to explore these issues, since the technocratic paradigm tends to give a secondary role to the social component within the system it intends to correct. However, to the extent that it is considered necessary to balance this component of the reality in which the risk reduction measures are inserted, the rational being comes to the forefront, and their acts have an ethical and legal dimension. For example, in a residential area subject to flooding, technical experts may establish that the most suitable solution is to build flood walls; however, the fact that the area has been occupied by people who are aware of this reality (often assuming that the public sector will come into their assistance) must influence the type of measures that are necessary, and may even call into question the priority of building such flood walls (see Box 10).

In general, given the complexity of reality in urban environments, both schemes are not antagonistic and may complement each other when it comes to offering explanations for the existence of risks in each specific case.

The altered equilibrium model

The altered equilibrium model is inspired by a conception of reality based on the general systems theory (Von Bertalanffy 1972). According to this model, land uses, including urban and periurban lands, evolve over time and follow dynamic mechanisms of adaptation to external conditions, especially climate, the size of the population, the level of wealth, and the technological context. As long as changes in these variables occur slowly and progressively (tens to hundreds of years), the adaptation process will also have these features and will be barely perceptible. These periods of slow evolution without phase transitions can be described as a state of quasi-equilibrium, with opportunities to explore new forms of adaptation to the underlying processes, with scarce traumatic events (or at least with traumatic events incorporated to traditional ways of life). However, such apparent equilibrium may be altered by two types of effects, which will be called impact effect and threshold effect:

A. The impact effect is associated with a sudden change in some of the involved external variables. This is the case of a quick transformation of climatic conditions, or the appearance of new technologies or consumer goods, capable of transforming land uses or traditional ways of life. This creates an impact that destabilizes the system abruptly, leaving little room for maneuver and exposing the population to certain risks of which it was not previously aware and for which it is not prepared.

B. The threshold effect occurs when, after a slow or rapid evolution, an internal variable of the system reaches a critical value from which the general evolution pattern that prevailed until then cannot be maintained without some qualitative features of the system being altered. This is the case when a stock-type variable, such as the population or the deforested area of a basin, becomes completely depleted or reaches its level of saturation. There may also exist internal processes in a system that generate phase changes, without them being linked to a specific threshold of a parameter.

When applying this generic model to natural risks in LAC cities, it is easy to identify examples where the equilibrium has been altered by abrupt variations (impact effect) in the exogenous variables that affect urban evolution:

- Demographic impact from migratory movements caused by active processes like war conflicts or forced emigration from rural areas, often linked to the globalization and technification of agri-food markets.

- Impact in the form of increased runoff (and, thus, a loss of water storage capacity of soil) derived from deforestation processes or from the implementation of single-crop farming over the last decades.

- Impact in the form of decreased water quality and, thus, decreased availability of drinking water, derived from a widespread use of detergents and chemicals, and from non-biodegradable solid waste.

- Impact of an increase in the hydraulic regulation capacity (dams) and in the capacity to transfer waters between basins for energy supply or production purposes. These infrastructures, which are at first glance beneficial for urban development, may carry negative effects in the long term.

Also, the threshold effect, linked to the concept of loading capacity, may be identified as the root cause of many of the risk problems detected in the studies conducted under the ESCI. The loading capacity of cities, and its associated limits, may be defined based on different parameters, including the following (for hydrometeorological risks):

- Percentage of altered area in the catchment areas of each city. Alteration includes both the area that has been deforested for agricultural use and the built area.

- Percentage of river channel length that has been altered. In this case, alteration refers to portions with strict flood control (which reduces the natural width of a river channel) or which have been buried.

- Percentage of occupation of floodplain areas, both in the urban area and in tributary basins.

The specific values of these parameters that serve as thresholds capable of leading to changes of phase in the relevant systems depend on each specific context and cannot, in general, be established beforehand. This subject will be explored in greater detail when addressing the classification of cities in section 5.2.

The rational being model

According to neoclassic economics, human beings are rational entities that make decisions to maximize their wellbeing. Following this principle, people would assume risks so that through luck or their wit (or the absence of other competitive advantages) they may get a reward they would otherwise not attain. Within this framework, assuming geo-climatic risks is the natural way of venturing for those who have no capital to invest other than their own lives and a few possessions they may have accumulated. While the wealthier invest in financial assets with different credit categories, being a-priori aware of their risk levels and being able to quantify it, the most disadvantaged do this same math literally exposing their existence[3]. This is the case of a family that settles in a flood-prone area with the idea of staying there temporarily, paying a low or zero rent, until they hypothetically save enough money to move to a better place. This is, in short, a bet in which it is the lives and basic needs of people that is at stake. The rational being model perfectly explains the link between poverty and risks of all kinds, as already noted by many authors (Krantz 2001; ADB 2012; Renos Vakis and Jamele Rigolini 2015; Hallegatte et al. 2014; Winsemius et al. 2015).

Albeit being backed by a long tradition of thought, the rational being model only partially explains the ultimate causes of the risks that affect cities and, especially, of the risks observed in emerging cities in LAC. Multiple factors can put the neoclassic economics model to the test and make it difficult to define a generic and universal conceptual framework for the problem – hence the alternative approach of the altered equilibrium:

- When it comes to risks, as in many other areas, people do not always have the necessary information to make informed decisions. In the previous example, of the family that settles in an area that is flooded every 50 years on average, this information is not usually known and, if it is, it is not available to those who may make the most use of it. Often, illiteracy and cultural poverty play a part in the problem, which is why they are often included as vulnerability factors. In the private land and house markets, there is the additional factor of the intrinsic asymmetry in terms of the information available to buyers and sellers. Under conditions of scarce information, it is hardly realistic to expect rational beings to behave as such.

- People, whether poor or rich, rarely behave in a rational manner when making decisions, especially when it comes to important issues and, especially, when it comes to risks. Scientists have identified at least three categories of thought that are tied to biased behaviors (Kahneman 2003): automatic thought, social thought, and thought based on mind models. Automatic though entails resorting to intuition and quick associations, instead of reflecting and reasoning in a broad framework; social thought imitates the behavior of other people, based on emotional affinity or simple gregariousness, without evaluating it thoroughly, and, finally, mind models are rigid schemes that operate automatically, often with deep sociocultural roots (e.g., the indigenous or female population of a given area may be subject to a race or gender-based barrier that modifies their behavior, usually in a negative way). These psycho-social aspects are increasingly being considered when it comes to designing and implementing policies, including those aimed at risk reduction (refer, for instance, to World Bank 2015).

- Even under the premise of full rationality and having all the available information at hand, hydroclimatic events involve a certain degree of epistemological uncertainty that cannot be estimated (see section 3.8). In certain cases, chance or the so-called black swans (Taleb 2011) will remain the most plausible causes of certain catastrophes.

The previously described dual model is related to and inspired by other classical models of risk production, like the Pressure and Release Model (PAR) and the Access Model (Blaikie et al., 2014). It also shares elements with the Sustainable Livelihood Framework as a poverty-reduction method, in both rural and urban areas; this method analyzes people's ability to earn a living in a broad sense, including economic, ecological, and social aspects (Krantz, 2001).

As can be seen, the general response to the problem of why people expose themselves (rational being model) or are exposed (altered equilibrium model) to risk opens a deep and complex debate with few practical results. Fortunately, the problem becomes easier to address when efforts are focused on a specific type of phenomenon within a specific geographical and historical context. To build a conceptual bridge between the dual model and the selection of specific risk reduction measures, it is useful to define a more analytical working framework based on risk construction mechanisms.

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[3] *From this perspective, the story of The Merchant of Venice (Shakespeare, 1600), where a merchant called Antonio accepts a loan from an usurer called Shylock on condition that if he does not repay it on the stipulated date, he must pay with a pound of meat from his own body, becomes a parable of the risk-poverty relation on a global scale.*

BOX 10

Historical evolution of the Juan Diaz river lower watershed in Panama city (Panama)

Problem

The Juan Diaz river watershed is currently one of the areas in Panama city with greater flood issues. Urban development in this city has led to significant shifts in land uses in this watershed and to the occupation of floodplains with landfills, housing developments and roads.

All of this has resulted in increased runoff and a dramatic decline in the hydraulic and water storage capacity of the river. These facts, along with insufficient drainage networks in urban areas and the impact of tides in lower lands, have led to more frequent and more severe flood events.

Methodology

To see the effect of such urban development on the flood risk, a hydraulic analysis of the high water levels has been done for four situations that coincide with other four stages of urban development in the watershed (Figure 34):

- Initial situation (Situation 1) of a river with only few interventions.
- Situation 2, which coincides with the opening of the Southern Corridor.
- Situation 3, where the Los Pueblos fills add to the previous conditions.
- Situation 4, which is the current situation, where the Metro Park fill and the opening of the existing channel add to the previous conditions.

Results

From the results of the hydraulic modeling of these situations (Figure 35), the following conclusions can be derived:

1. Flood levels have been increasing in the study area as the different urban development works have been completed.
2. Overall, from Situation 1 to the current situation, the high water levels in the area have reached 31 cm for T=10 years, 32 cm for T=20 years, 56 cm for T=100 years, and 70 cm for T=500 years.
3. If we compare the levels for Situation 1 and 4, we may also see that floods frequency has also increased. The levels that in Situation 1 were reached with a 20 year flood are nowadays exceeded with T=10 year floods.

Table 14 summarizes the sequence of level increases that have occurred with the different works conducted in the lower area, in relation to the initial situation considered.

WORKS	LEVEL INCREASE (CM)			
	T= 10 YEARS	T= 20 YEARS	T= 100 YEARS	T= 500 YEARS
CONSTRUCTION OF THE SOUTHERN CORRIDOR	+22	+30	+32	+37
CC LOS PUEBLOS FILL	+3	+4	+4	+2
METRO PARK FILL	+27	+27	+29	+30
TOTAL	+52	+61	+65	+69

Table 14 | Sequence of increase in water levels from situation 1 to 4.

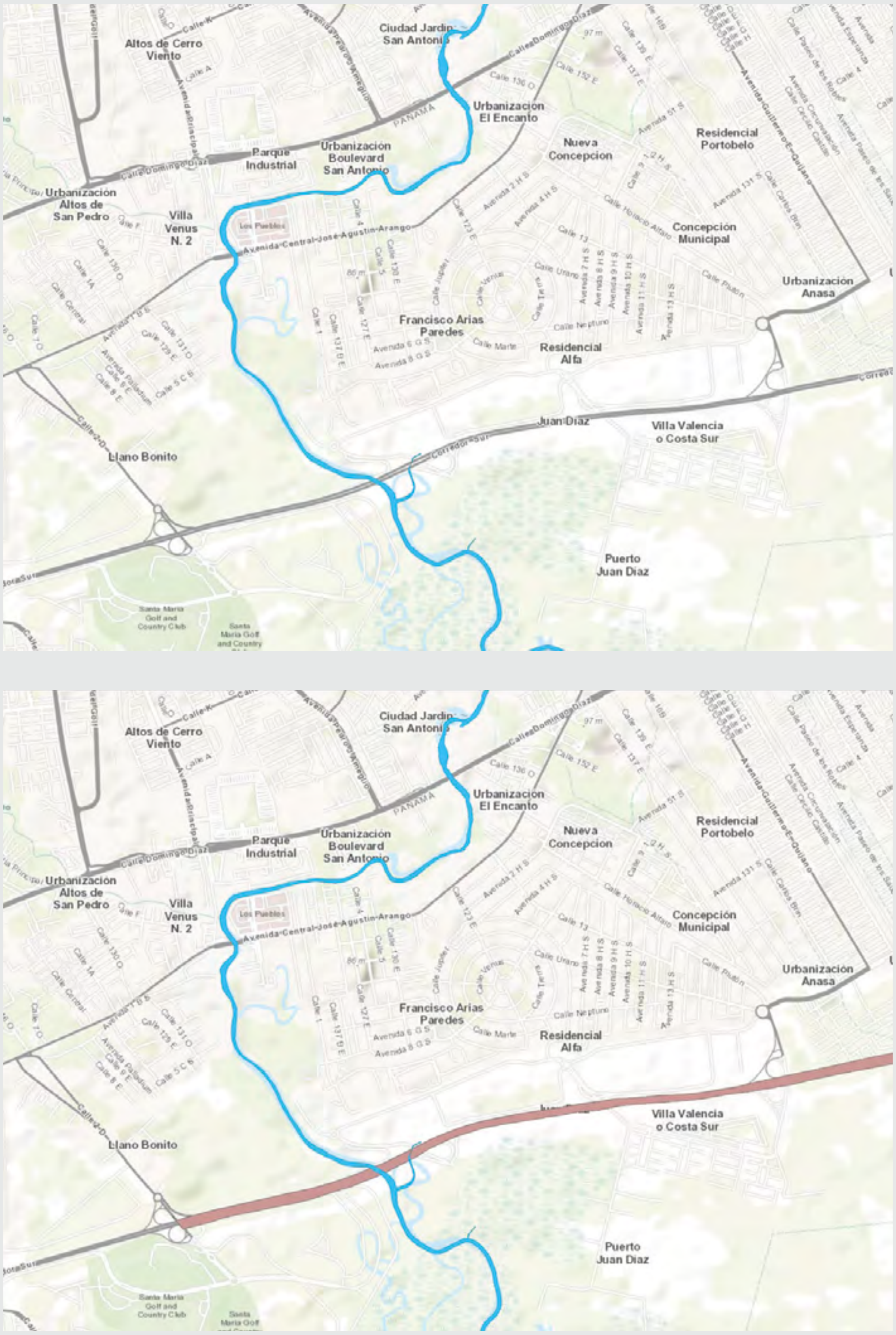


Figure 34 | Different calculation scenarios (Situations 1-4).

Figure 34 | Different calculation scenarios (Situations 1-4).

Figure 35 | Longitudinal profile showing flood levels in Situations 1-4.

5.2 Flood risk construction mechanisms in LAC cities

With the dual model, hydroclimatic risk issues can be addressed from an ontological perspective but cannot be framed in terms of space and time, and thus we cannot establish what in this context is called Risk Construction Mechanisms (RCMs). In this section, we will identify and characterize some of the most relevant RCMs for different types of cities, in an attempt to provide information that serves as a bridge to establish the most appropriate reduction strategies and measures in each case.

The RCMs are defined as concrete cause-effect chains that start from exogenous causes on a regional or global scale and transfer them to the scale of a city, identifying prevailing physical and socioeconomic processes capable of modifying local risk conditions. The RCMs can either merely transmit a disturbance on a larger spatial or time scale to the sphere of risks in a local environment (RCMs as a downscaling mechanism), or include more complex feedback loops on a local scale, as a result of the reactions that take place in response to the increased risk, either perceived or already materialized through a catastrophic event.

To characterize RCMs, we need an analytical conceptual framework which naturally accommodates the main cause-effect chains that lead to risk production in any city. Figure 36 shows a generic flow chart that presents and relates the abstract components of risk, as already presented in Chapter 1, in the form of a chart that is similar to those used in systems theory. Based on this approach, the two large risk components (hazard and vulnerability), as well as the risk itself, are state variables that can potentially be quantified; they relate to each other through certain physical and socio-economic processes, which are specific to each RCM. In this chart, RCMs are more clearly identified with concrete and typified sequences of inter-relation between hazard and vulnerability factors, which need to be specified for each city and type of risk.

The general scheme for defining RCMs in Figure 36 has been conceived to analyze and interpret risks on a city scale, so it clearly differentiates the exogenous variables (in both the hazard and the vulnerability) in local processes, although this differentiation may also be useful to explore RCMs on a regional or country scale. By identifying risk factors on a larger scale as imposed exogenous variables, which are not attempted to be explained within each RCM, it is possible to focus the attention on how those global boundary conditions are transferred to each urban context, avoiding an analysis of the dynamics of processes on a larger scale. The influence, and thus the potential feedback effect, of urban processes on the regional or global context has also been omitted, although it is evident that any climate change mitigation strategy (in the sense adopted by the IPCC, i.e. GHG emissions reduction) is based on the sum of parts.

From the perspective of floods – the most characteristic risk addressed in this document – the main sources of hydroclimatic hazards on a regional or global scale are dominated by a more or less sudden change in climate that is induced by human beings:

- Sea level rise.
- Alteration in precipitation and temperature regimes.
- Changes in the typical frequency and tracks of hurricanes.
- Change in the type of vegetation and degree of vegetation cover in basins.
- Land use changes in river basins with alterations in the hydrological regime, also as an effect of human activities, without climate change being necessary.

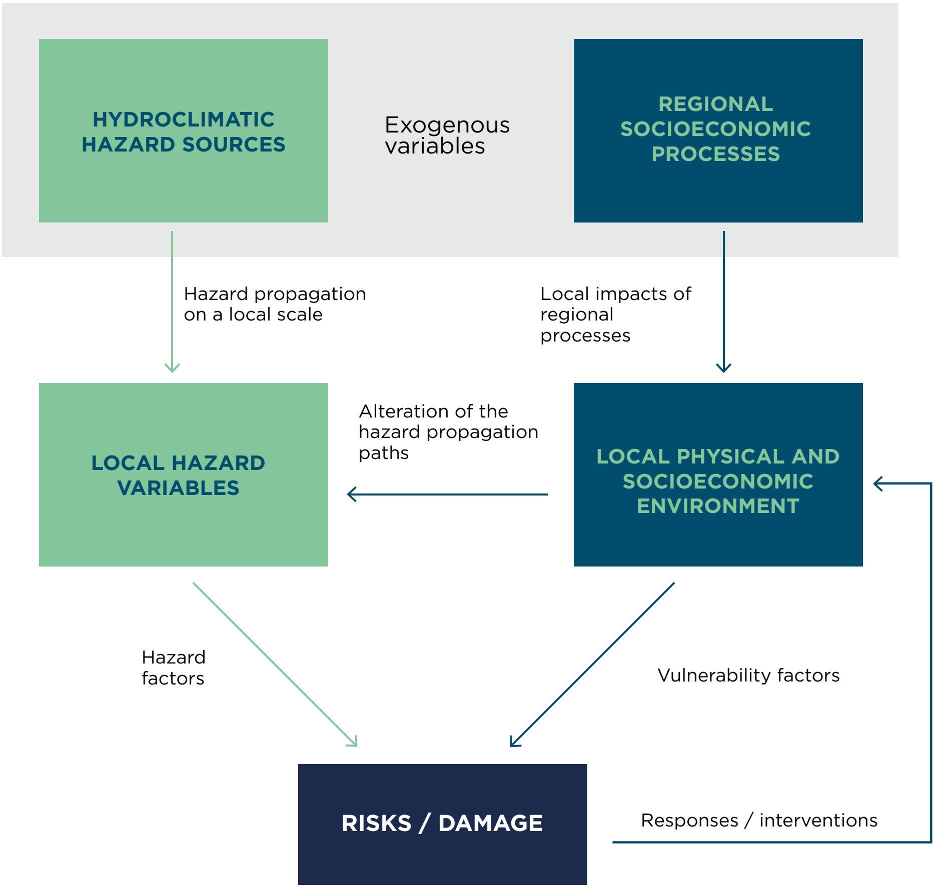


Figure 36 | General scheme to define risk construction mechanisms.

Furthermore, the most important exogenous socioeconomic processes, which directly or indirectly increase the vulnerability and exposure of cities, are the following:

- Processes of migration from rural areas to cities triggered by different causes: agri-food crises (of a local origin or derived from global processes), armed conflicts, productive model shifts, etc.
- Increase in the poverty rate and macroeconomic deterioration on a national or regional scale as a result of the competition dynamics on different scales.
- Political, institutional and governance crises in the country where the city is located or in nearby countries.
- Increased social inequality, even in a context of macroeconomic growth, due to a failure or absence of redistribution policies.

These hazard and vulnerability factors, which operate as boundary conditions, have a specific and different impact on each city depending on their physiographic characteristics, and climatic and sociocultural features, as well as on concrete decisions taken by individuals and institutions. Therefore, each city, as a dynamic system, will respond to the aforesaid disturbances with modifications in the physical reality, as well as in the cognitive reality or noosphere: institutional and legal framework, planning, mind models, etc. It is precisely in this translation from the global into the local and particular conditions of a city that the RCMs must show their usefulness to identify favorable feedback loops for risk reduction. Within this framework, risk reduction measures are rational and planned responses that aim at generating negative feedback loops (i.e., a reduction) in those processes that are generating risks.

It is important to highlight that such planned actions, together with automatic and spontaneous responses to risks, feedback a complex system, since risk/damage reduction must necessarily go through a modification of the physical and socioeconomic environment, which may in turn modify the vulnerability factors and the physical pathways of the hazards.

To characterize the main RCMs that take place in LAC cities based on the experience of the ESCI it is useful to adopt a classification of cities bases on physiographic and geomorphological criteria. With this classification, it is possible to extrapolate the experience and the results obtained in the ESCI to other LAC cities, apart from conducting a case-by-case analysis. While any classification of cities is necessarily subjective and, in a way, arbitrary, the practical advantages of establishing these categories are considered greater than their deficiencies and limitations. For the purposes of this document, four large types of cities have been identified in terms of flooding and erosion risk in LAC:

1. Shallow-slope coastal city.
2. Moderate to steep-slope coastal city.
3. Inland city located in the head of a watershed.
4. Inland city located in an intermediate portion of a watershed.

The reason why the only classification criterion is a physiographic one, with no other socioeconomic and cultural criteria being considered, is merely statistical: the available sample of cities does not cover a sufficiently wide range of socioeconomic and development levels so as to introduce some other type of criteria. Finally, it should be noted that when this classification is proposed from a hydroclimatic risks perspective, it is inevitable to generalize and, thus, simplify the physiographic reality of cities: most of the cities included in ESCI – maybe except for the smallest ones – have multiple sectors or nuclei with different characteristics. In this case, the proposed classification should apply to each of those nuclei, rather than to the city as a whole, and even then, there will always be neighborhoods that will be the exception to the rule.

It has been observed that most of the cities studied fall in one of the aforementioned categories, which points at the fact that those that do not fit in any of them are, generally speaking, less prone to be subject to hydroclimatic risks. Among the missing categories are, without making an exhaustive account, cities located on rock massifs (coastal or inland) or in endorheic watersheds with predominantly underground flow.

A descriptive card has been prepared for each of the four categories of cities or urban nuclei with information that is relevant for each type, structured according to the following parameters:

TYPE OF CITY/URBAN SECTOR: this is the main classification of a city for the four types mentioned. There is a card for each category (four in total).

DOMINANT PHYSICAL PROCESSES: it gives information on the importance of the dominant hydrological mechanisms, ranked from one to three (from lesser to greater importance); this is relevant when it comes to proposing general risk reduction strategies. For simplification purposes, only three basic mechanisms are considered:

1. **Transportation.** It refers to the transportation of water on the surface and by gravity, through both river and urban drainage networks. It is a quick runoff water removal mechanism, but it requires a topographic slope and an appropriate point of discharge.

2. **Storage.** It entails compensating water transportation capacity with water storage capacity in certain areas aimed for that use. Implementing this mechanism means allowing a planned flooding.

3. **Infiltration.** When the land has enough conductivity and is not saturated, the infiltration mechanism enables moving surface water to a downstream aquifer, preventing above-ground flooding. This mechanism is usually linked to a slow flow (low transportation capacity) and to the storage mechanism.

SUB-TYPES: it is a classification according to sub-types of the four city types considered. It is used to specify certain features according to the following criteria. It does not intend to be exhaustive and could be extended by incorporating new case studies.

GENERAL CHARACTERIZATION: it is a detailed description of the specific features of each type of city that differentiate them from the rest.

ESCI EXAMPLES: a list of the ESCI cities that represent each type of city, with their associated sub-type.

DOMINANT RCMs: based on the conceptual framework presented above, a description of some of the main and characteristic risk construction mechanisms for each type of city is provided. The list of mechanisms does not intend to be exhaustive, but it is certainly representative.

POTENTIAL RISK INDICES: based on the main RCMs for each type of city, systems of potential risk indicators can be defined. Such systems are generally based on the degree of disturbance of the component of the physical medium that accommodates or supports the dominant processes. Based on these indicators, it is possible to estimate the seriousness of the problems affecting a city, without making calculations. Potential risk indices work as an initial approximation to risk and give and idea of how well or poorly prepared is a city or urban sector to reduce risk. They are closely tied to the concept of carrying capacity and threshold effect, as already described in the previous section, within the altered equilibrium model.

GENERAL INTERVENTION RECOMMENDATIONS: they are aimed at informing the design of risk reduction measures for each type of city and, sometimes, for each sub-type.

LESSONS LEARNED FROM EMERGING AND SUSTAINABLE CITIES: they include other pieces of advice and warnings derived from ESCI in connection with critical design aspects or common mistakes that have been identified.

This classification includes multiple subjective discrimination criteria, which may imply that, in some cases, a certain city may be half-way from two of the proposed categories. Far from invalidating the proposed classification, this circumstance is simply an invitation to combine the most pertinent recommendations and criteria from each possible typology. In coastal cities, a shallow slope refers to certain geomorphological conditions of the territory which generally involve slopes that are lower than 1:200 V:H (0.5%) o, more strictly speaking, 1:500 V:H (0.2%). As for inland cities, the boundaries between the upper watershed and the middle or lower watershed – even if these terms are commonly accepted – tend to be diffuse, without this invalidating the aforesaid. Reference is also made to cities with a main river, as opposed to others with multiple smaller streams without a clear hierarchical relation. It has been found that this differentiation is usually valid for practical purposes, without emphasizing other advantages.

Type of City/Urban sector

Shallow-slope coastal (SSC)

DOMINANT PHYSICAL PROCESSES:

Belize city (Source: Google Earth)

Subtype

- City located in a delta area with a main river (SSC-R).
- City in a low land without a river (SSC-W/O R).

General characterization

In SSC cities, the natural terrain is very close to the sea level, and its slopes are often lower than 0.2%. From a geological viewpoint, they usually are recent alluvial deposits, either directly formed by a river action and its solid inputs (deltas), or indirectly formed by the accumulation of coastal sediments carried from a remote source (bars, spits, landfills, etc.). They are natural spaces with a strong land-sea interaction, subject to a combination of physical processes that generate variable geometries in the territory. Flood hazard sources in these environments are, at first glance, three: the sea level, the river level (in the SSC-R) and local rainfall. The three processes are usually not statistically independent but somewhat correlated, so the risk should be formally analyzed using multi-variate analysis techniques with non-Gaussian joint distributions. In certain cities, or for certain urban sectors, simplifying hypotheses may be adopted.

The traditional types of settlements in these environments are either scattered and mobile (nomad, transhumant), or fixed, based on the use of elevated building types (primitive houses built upon stakes), systems of channels with fills, and agriculture based on camellones (raised beds with irrigation channels). The damage from flooding in this type of cities is often tied to water levels, since speeds are slow, except in specific points. Therefore, economic and indirect damage (including damage to public health and social segregation in the most affected areas) dominate over direct human damage.

ESCI examples

- Campeche (Mexico). Sub-type: SSC-W/O R.
- Cumana (Venezuela). Sub-type: SSC-R.
- Belize City (Belize). Sub-type: SSC-R.

Dominant RCMs

RCM-1: A rise in the average sea level as a result of climate change combined with alterations in the levels and precipitations regime increases the frequency and scale of floods in these cities. In addition to the direct inflow of sea water, there is the problem related to the drainage of drains and streams, which usually overflow. This results in the deterioration and segregation of urban areas that have not been built on a fill bed, usually populated by medium- to low-income people or informal settlements. For the same reasons, the lower coastal areas tend to depopulate or to be occupied by informal settlements.

RCM-2: When this type of cities are exposed to a rapid increase in population due to regional processes, their carrying capacity is relatively low in terms of urbanization rate or other similar indicators (see potential risk indices), so they tend to collapse. This is mainly due to a reduction in the water storage capacity, rather than to an increase in the impervious surface. Population growth usually requires densifying transportation networks and increasing parking spaces, which often entails a decrease in, or the burying of, channels, green spaces, marshes, mangroves, and any space capable of storing water. The progressive reclamation of new areas that are fit for building worsens the conditions in other areas that are already consolidated, reducing their value and promoting even more landfills.

RCM -3: In certain cities of this type, the extraction of water, gas, or oil from the underground (sometimes from distant extraction points), results in soil subsidence, with an effect that is equivalent to a permanent sea level rise. In other cases, the creation of linear transportation structures that require considerable land filling and support traffic loads, like a highway, results in the consolidation of the surrounding soil, putting bordering areas at risk of flooding.

Indices of potential risk

- Built area ratio (built area/total area).
- Ratio of green areas and of water surface areas (green and blue area/total area).
- Retention capacity index (total free volume/volume associated with runoff from a 1-hour rain event with a 10-year or similar return period).

General intervention recommendations

Due to geographical conditioning factors, SSC cities have a poor natural capacity to quickly remove storm water and water from the overflow of their internal drainage network (rivers, streams, and artificial drains). The only mechanism to reduce temporary flooding is storage, that is, temporarily flooding an area of land so that the excessive volume, which is appropriately distributed, generates tolerable levels of flood; alternative mechanisms of infiltration and adduction are often insufficient. In these environments, there are two basic risk mitigation strategies:

1. Solutions based on imitating and boosting the natural mechanism for selective water accumulation. For this, both natural areas within or around the city (wetlands, ponds) and areas that are fit for this purpose (parks, roundabouts, parking areas) can be used. This often requires reassigning uses within an urban grid, as well as recovering, protecting, and connecting the natural spaces most fit for this purpose.
2. Technological solutions to increase the water removal capacity. When there is limited capacity to generate storage space within the urban area, there is no other option than boosting the existing natural mechanisms, especially storage and adduction mechanisms, through artificial (technological) means. This requires building flood water storage tanks and pools equipped with pumping facilities. In the extreme case of applying this principle to land permanently located below the sea level, a polder-type solution is used, although this is usually an exceptional and temporary solution.

Lessons learned from emerging and sustainable cities

The main feature of this type of cities is their high vulnerability to a sea level rise. Also, in SSC cities a certain confusion over the most suitable urban drainage model is usually observed. Often, this type of cities tend to develop conventional drainage systems that imitate those of other cities and that are based on gravity pipes. While such systems may be appropriate in areas with sufficiently sleep slopes, they do not naturally respond to the dynamics of this type of territory and tend to collapse when events of a relatively large scale occur, or as the population grows.

Other cities have ancient channel networks whose basic function from a flood management perspective is not to remove but to store water and connect flood storage areas (apart from other functions like navigation or waste disposal). However, in recent times, these elements have been turned into storm reservoirs and drains of conventional urban drainage networks through works to reduce their section, often by adding a concrete lining, burying sections and entrenching them to generate useful urban space. With these measures, their storage capacity and interaction with neighboring areas have been reduced.

One of the problems resulting from implementing conventional draining systems in SSC cities is that, even if there is a certain hydraulic slope that is theoretically fit for moving water, the low flow rates result in the settling of sediments and waste, which end up clogging the pipes. Cleaning, especially in buried sections, is costly and difficult, so it is usually not done correctly. SSC cities are, by their very nature, not well prepared to manage natural sediments and solid urban waste in general, but implementing a drainage model based on narrow or inaccessible elements is an additional mistake that makes maintenance works even more difficult.

Wet green areas with water storage capacity (mangroves, marshes, wetlands, etc.) have a critical role in this type of cities, so they need to be recovered and preserved, notwithstanding private interests. It is necessary to encourage the creation of parks and large public spaces that can be flooded in case of extreme events and, where possible, take advantage of low and concave areas where the territory had this natural function in the past.

Type of City/Urban sector

Moderate to steep-slope coastal city (MSSC)

DOMINANT PHYSICAL PROCESSES:

Trujillo (Peru). Source: Google Earth

Subtype

- Steep-slope city with a dominant river channel (MSSC-R).
- Steep-slope city with several coastal streams (MSSC-W/O R).

General characterization

These are coastal cities sited on firm ground with a moderate to steep slope towards the sea. In this configuration, the sea level rise (temporary or permanent) only affects the streets that are close to the coastline, but not those that are inland on higher grounds. These cities are fit for large consolidated urban settlements, since runoff water from both rivers and local rainfall naturally flows towards the sea. The dominant hydrological mechanism is usually surface runoff, although it is usually combined with a certain degree of infiltration and storage. The dominant hazard factors are local rain events, and river and stream flows, which in the MSSC-W/O R sub-type cities can be analyzed as coincident processes or, at least, as highly correlated processes. For MSSC-R with a large river, it is advisable to differentiate riverine floods from flood events caused by local rainfall. The coastal area in these cities may, in general, be analyzed in terms of marine risks (wave overflow, coastal erosion) independently from the rest of the city. In this type of cities, and especially those with large rivers (MSSC-R), overflow waters may have considerable speeds, which usually increases economic losses and, especially, human damage.

ESCI examples

- Port of Spain (Trinidad and Tobago). Sub-type: MSSC-W/O R.
- Trujillo (Peru). Sub-type: MSSC-W/O R.
- Bridgetown (Barbados). Sub-type: MSSC-R.
- City of Panama (Panama) Sub-type: MSSC-W/O R.
- Santa Marta (Colombia). Sub-type: MSSC-R.

Dominant RCMs

RCM-1: Population growth generates a direct increase in the surface area of the urban patch. When the expansion area of a city is limited in the direction of the coastline, which may happen because of the presence of landforms like mountains or large rivers, there is no other option but to grow inland, following an axis that is perpendicular to the coastline. The increase in the impervious area generates an increase in peak flows and runoff accumulation in the lowest areas which, if not offset through sewer networks, leads to frequent floods and the deterioration of the urban space in those sectors, mostly affecting the neighbors located on the seafront. As a result of this, the value of these areas declines and there is increased preference for periurban land plots, creating a feedback loop that weakens the options for a model with a dense city with a well-defined center. Also, this risk construction mechanism may prevent the consolidation of a quality seafront that takes advantage of the sea presence (for both public and private use), due to both frequent floods and poor water quality.

RCM-2: When migration to a city is triggered by acute processes like war conflicts or food crises, a large proportion of the new inhabitants is usually formed by people without economic resources to afford a house, who nevertheless choose to be close to the activity centers to be able to develop a livelihood of their own, generally within the informal economy. In MSSC cities, the available spaces in the already-consolidated urban space are often located on riverbanks that are subject to floods and in unstable slopes near nerve centers. The occupation of these spaces with informal housing, usually facilitated by a restrictive urban planning (high protection of areas with a strategic location), generates risks for those houses, which are usually exported to more distant areas. Once informal settlements have appeared, a system of real estate organization and management is created outside the regular real estate legal system, which is very difficult to reverse.

Indices of potential risk

- Relative capacity of the urban drainage network: design flow of the drainage network relative to the flow generated by rainfall associated with a certain return period (e.g. 10 years).
- Water storage and retention capacity: surface area of green spaces and retention elements relative to the total urban surface area.
- Degree of occupation of floodplains of natural rivers within the urban environment.

General intervention recommendations

Flood problems in this type of cities are usually successfully solved through a combination of the following:

1. Implementation of conventional urban drainage networks, usually integrated in a combined sanitation system which is also fit for removing waste waters.
2. Deviation or impoundment of streams and small watercourses in their upper sections before penetrating the urban area. Impoundment spaces can be created, or otherwise streams can be deviated to a main river or to less vulnerable areas.
3. Restoration and improvement of the hydraulic capacity of river corridors in urban sections. These measures usually combine urbanistic improvement with a widening of the river space in general and solutions in critical sections (bridges, narrowing portions, meanders, etc.).
4. Seafront stabilization works. They usually include the consolidation of a promenade or a jetty, usually coupled with a coastal intercepting sewer that collects and removes stormwater runoff.

Lessons learned

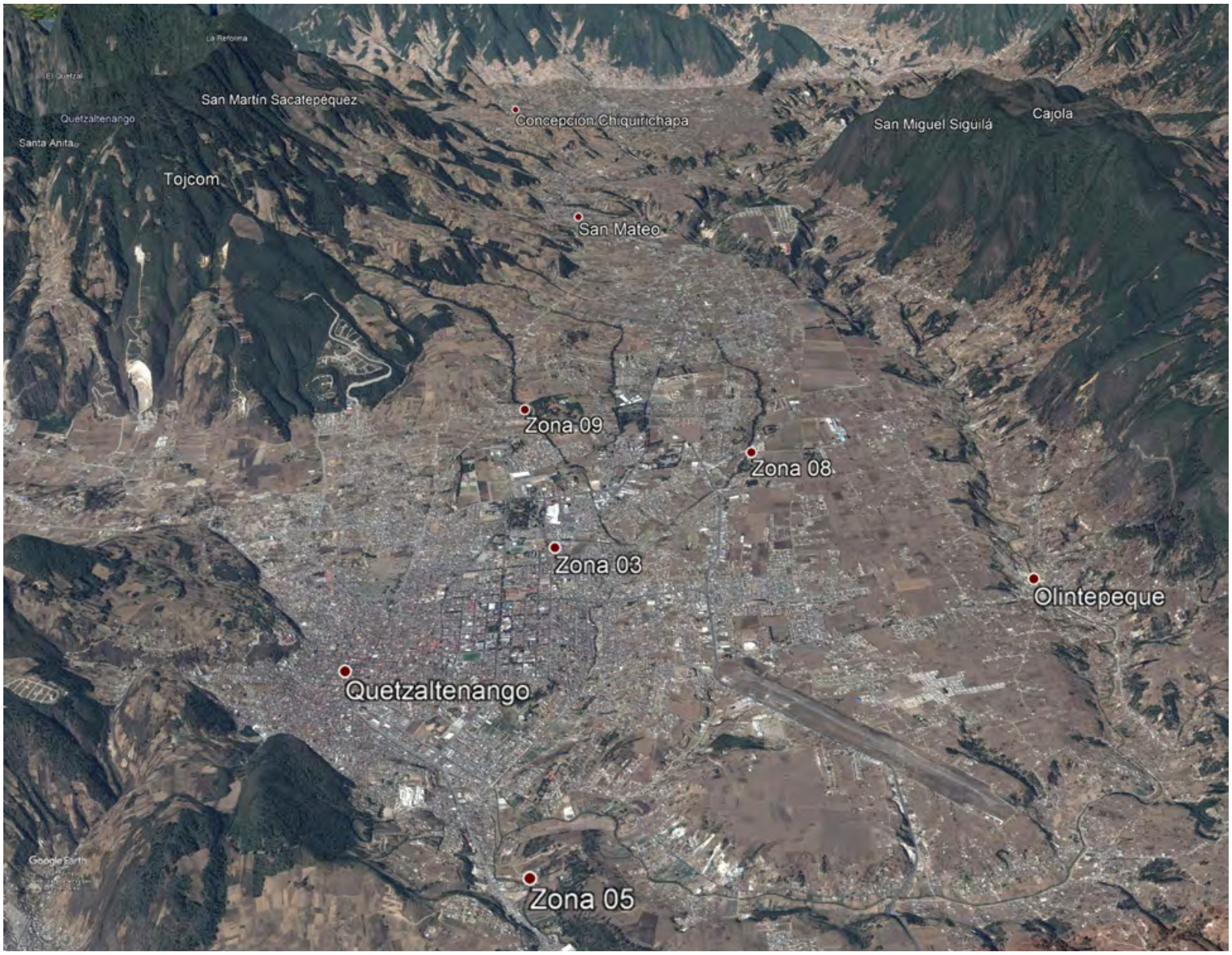
MSSC cities are relatively well prepared to improve their condition in terms of floods, although this requires significant capital investments, which are also coupled with considerable maintenance and operating costs. It is therefore necessary to have urban water cycle management companies with sufficient capacities and financial resources, which is not feasible without implementing a fee (for sanitation and sewer services) that must be efficiently collected, considering the social and economic circumstances of each city. Ultimately, to solve this type of problems in cities, in terms of both floods and sanitation, it is necessary to solve governance and taxation problems, which are usually far more complex than technical problems.

In addition, in cities with a great inflow of migrants with scarce resources, urban planning must contemplate the supply of non-building land that remains available for the informal market, and set clear and realistic criteria in terms of how to address this problem before its scale is so large that it cannot be addressed.

Type of City/Urban sector

Inland in watershed head (IWH)

DOMINANT PHYSICAL PROCESSES:



Quetzaltenango (Guatemala) Source: Google Earth

Subtype

- City in an area where several secondary streams meet (IWH-W/O R).
- City in an area where one or more main rivers meet with several secondary streams (IWH-R)

General characterization

This type of city is located in the upper watershed of a river, generally an alluvial valley where several minor streams and rivers meet as they go down the limiting slopes and usually generate a larger river at some point downstream. Sometimes (sub-type IWH-R) there is already a main river to which another main river or a network of smaller streams incorporates. While the slopes of rivers and streams are usually significant in their initial sections, in the area where they meet there is a deceleration of the flow and an accumulation of sediments, creating shallower spaces with varying slopes in different areas.

The dominant hydrological mechanism in the slopes around these cities is surface runoff, modulated by the presence of vegetation and a soil layer with varying depth. In the central area of the valley, all the mechanisms can combine: river channels carry part of the water but tend to overflow due to the lower slopes, creating water accumulation and infiltration areas (both phenomena are usually linked in these cases) in floodplains located in the riverbanks. In certain areas adjacent to relatively steep slopes, flood and land slide risks combine into different phenomena (hyper-concentrated flows, avalanches of rocks, landslides, rockfalls, etc.).

The dominant hazard factors are local rainfall and river and stream flows, which in the IWH-W/O R sub-type cities can be analyzed as coincident or highly correlated processes. As for IWH-R cities, where a major river exists, it may be necessary to differentiate riverine floods from floods caused by rainfall.

As in the previous category, in these cities overflow waters may have very high speeds in certain areas and may cause severe economic and human damage. In the valley surface with a lower slope, human damage tends to be less significant, but the affected area tends to increase considerably.

ESC examples

- Santa Ana (El Salvador). Sub-type: IWH-W/O R
- Quetzaltenango (Guatemala). Sub-type: IWH-R
- Xalapa (Mexico). Sub-type: IWH-W/O R
- Cusco (Peru). Sub-type: IWH-R

Dominant RCMs

RCM-1: Urban development in the shallow valley area derived from a progressive population growth is inconsistent with the spatial fragmentation of the territory associated with an extensive river network comprising multiple smaller streams in the shape of a fan or with irregular shapes. Due to streets and roads being built roughly in the form of an orthogonal grid, it is necessary to bury or bridge numerous passages of water, which are progressively reduced, filled or grouped. This consolidation of streams, done based on local criteria and without a global vision, ends up drastically reducing the hydrological response capacity of the territory, which ultimately lacks mechanisms to remove the water that it receives from the surrounding area, except by flooding the urban space. This is a cumulative effect that materializes mainly in areas located in lower elevations, usually near to the junction with a main or larger stream.

RCM-2: Population growth, together with the materialization of the processes described in the previous mechanism (deterioration of historical areas) leads to the occupation of the hillsides limiting the valley: the population with a certain purchasing power tends to occupy the hillsides with shallower slopes and better weather conditions, while the most disadvantaged groups establish informal settlements in the rest of the areas. In both cases, an increase in the stream flows associated with extreme rainfall in the lower areas of the city occurs as a result of the increased impervious surfaces in tributary watersheds, which increases flood risk in those watersheds. Floods often occur in historical districts which had not suffered this phenomenon until recent times, resulting in a decrease in the value of that land, socio-economic segregation, and fewer opportunities to take advantage of cultural heritage through tourism. The population with a certain purchasing power that used to live in historical districts or nearby areas ultimately opts to move to the suburbs, which feeds back the risk-production loop.

Indices of potential risk

- Degree of alteration of the hillsides sloping into the city (altered area over total area).
- Degree of alteration of the river network (altered length over total length).

General intervention recommendations

1. If possible, natural stream and river channels must be fully or partially restored to their most recent alignment and their associated protection perimeters. Oftentimes, the presence of buildings or infrastructures makes it difficult to maintain the original alignment of river and stream channels, but in general the natural network should inspire the potential alignments of the new urban runoff water intercepting sewers, which should be sized adopting proper safety margins, considering the potential effects of the urbanization of periurban areas.

2. In those sectors where the alluvial geomorphology has generated a concave topography with low points without outlets, it is necessary to increase the capacity to store water without generating risks, creating green areas or even storm water tanks.

3. If the geometry of the valley is fit for this, the possibility to intercept and group as many streams as possible should be analyzed; their waters should be moved to a main river with sufficient capacity or to some point downstream with lower risks.

4. Finally, the number of housing developments in the slopes should be controlled, and the conservation of vegetated natural land should be increased. It is important to guarantee that the new expansion areas, especially those for the wealthy, include runoff storage and management mechanisms so that conditions do not worsen in the lower areas. In new building areas, especially those accommodating the upper and middle classes, the use of green

Lessons learned

The cities of this type may have a complex topography resulting from an active sediment dynamics and the co-evolution of several alluvial fans originated from different slopes, which, in certain cases, prevents the visualization of a conventional drainage system based on sewer networks with a fixed alignment. Also, if there are slopes with active volcanic cones, the associated river network can be diffuse without well-defined channels, which makes it difficult to collect water upstream. Due to these and other reasons, in this type of cities, the design of conventional drainage networks may be less intuitive than in other cities with a dominant flow direction.

In these environments no single rules exist, but in general it is advisable to take advantage of the available slopes, if possible imitating natural river and stream channels, to remove water by gravity. There will always be areas where this model is not viable and non-conventional drainage solutions should be applied to boost water retention and filtering capacity, but it is important to bear in mind that gravity flow is always the best option, if available. In this type of cities, the sediments carried by runoff water may be significant, so any solution designed should be silting-proof, which means it is important to consider the solid load in the design phase (creating settling pools, placing grids, guaranteeing slow flow rates, etc.) and in the maintenance phase (accessible or open-section sewers). In this type of cities with high seismic risks, non-rigid drainage solutions should be considered and, if possible, they should be open-air.

Type of City/Urban sector

Inland city in the middle section of a watershed with a main river and tributaries (IMS)

DOMINANT PHYSICAL PROCESSES:

Huancayo (Peru). Source: Google Earth

Subtype

- City in an active river terrace (IMS-AT)
- City in an inactive or decoupled main river terrace (IMS-IT)

General characterization

This type of city is in the middle section of a large river where different smaller tributaries drain their waters. In this cities, the main river is a structuring element of the territory capable of affecting connectivity and segregating the urban space. The geomorphological nature of the banks in each area greatly determines the type of relation between the river and the cities and the associated risks. The areas on active terraces can often be subject to floods, but they also offer clearer urban integration opportunities; on the other hand, elevated banks (due to either being abandoned terraces or being located on rock outcrops) generate a more distinct barrier effect, but do not pose hydrological risks (although in some cases they do pose geological risks: landslides, erosion, rockfalls, etc.).

The dominant hydrological mechanism is surface runoff, although some riverbank areas can be associated with depositional processes (abandoned meanders, old river channels in large valleys) where storage and infiltration occur. One of the most characteristic aspects of these environments is the action of small tributaries that drain their waters into a main river, whose hydraulic capacity is usually more dependent on the water stage in the main river than on its own slope and flow.

In IMS cities, the dominant risk factor is the flow of the main river, which is usually associated with regional precipitation fields and hydrological processes; their study therefore exceeds the urban sphere. As a secondary hazard factor, maybe the most important one in some specific areas, there is the local rainfall, either directly on the city or propagated trough streams and secondary rivers.

This type of cities may suffer large catastrophic events if the main river overflows or deviates from its channel. In the case of big cities with moderate to steep slopes, economic and human damages can be significant.

ESCI examples

- Huancayo (Peru). Sub-type: IMS-AT (left bank) and IMS-IT (right bank).
- Tegucigalpa (Honduras). Sub-type: IMS-AT (prevailing) and IMS-IT (historic district).
- Santiago de los Caballeros (Dominican Republic). Sub-type: IMS-AT (northern meander area) and IMS-IT (El Yake Outlook and golf course area).

Dominant RCMs

RCM-1: Population growth, and especially the inflow of migrants with little economic resources, leads to the occupation of river terraces that are subject to flooding which had historically been designated as reservation areas with non-consolidated land uses. In some cases, these areas are protected with retaining structures (walls, embankments, gabions) that lead to an acceleration of the flow with local erosion processes, which transfers the problem downstream.

RCM-2: In order to reduce the space occupied by a main river in an urban grid, a narrow channel is built for the river, which generates increased water levels for extreme flows. This impacts the hydraulic and geomorphological working conditions of the main river and its tributaries. The latter specifically experience higher water levels and local water head losses at their mouth, as well as a flow deceleration, causing accumulation of sediments, which can raise the riverbed level. These chain processes transfer the flood risk in the main river channel to the banks of said secondary streams or rivers, usually located in consolidated urban areas.

RCM-3: Building a dam in the catchment of the main river results in a reduction of the flows regime (both liquid and solids flows) creating a feeling of safety by transforming areas that were traditionally subject to flood events into virtually safe land. However, an improper operation of the reservoir, where floodwater storage is secondary as compared to the production of energy or consumptive uses, may result in catastrophic river floods. The technological risks associated with the reservoir management may be higher than the hydrological risks under a natural regime, with the aggravating factor that the population's perception of risk has declined, while their exposure and vulnerability have increased.

Indices of potential risk

- Degree of alteration of the main river catchment area.
- Percentage of the urban land located in active river terraces.
- Degree of alteration of the main river channel near and within the city.

General intervention recommendations

For this type of cities, it is convenient to define and agree upon a viable and consistent model of city-river relation that integrates the natural characteristics of the territory, risk factors, urbanism and socioeconomic segregation; such model must at least condition – and in certain cases structure – the land management master plan. In many cases, it is convenient to limit the river corridor – but without excessively reducing its available space – including expansion areas for floods, relying on an analysis of the fundamental geomorphological processes, considering the river as a whole that comprises not only water, but also sediments. Works in the river channel, whether cross-wise or longitudinal, must be designed contemplating potential variations in the plan and profile of both the section where the works are located and other related areas.

Lessons learned

A common feature of many IMS cities in ALC, including the ESCI cities, is the low interrelation between the river and the city, and that their inhabitants tend to live with their backs towards their rivers. This is contrary to what happens in Europe and in some areas in Asia, where urban river corridors are consolidating as revitalizing and structural backbones of the public space, with a differential value. The lands located on riverbanks in many LAC cities offer significant income generation opportunities, both at public and private level, but the process is slow and requires triggers that are usually linked to public investment. However, risk reduction is just one of the aspects that need to be addressed in a project of this type for it to be successful. Other necessary aspects are wastewater treatment, solid waste management, citizen safety, institutional capacity, and tax mechanisms to cover operating costs.

5.3 Risk filters and indicators

Throughout chapters 1 to 4, we have outlined quantitative methods to calculate different types of risks, the final result of which can be expressed as dimensionless indices (average annual loss as a percentage of the GDP, average fatality rate per million people and year, etc.). Risk indices are useful to make different types of comparisons:

1. Comparing different risks in one same city in order to establish which one should be addressed first.

2. Comparing different cities as to a specific type or group of risks to establish which is most affected.

3. Comparing hydroclimatic risks in a city against risks whose characteristics or consequences are similar (geological, technological, biological risks, etc.).

However, from a global and cross-sectoral perspective, the interventions to mitigate the risks that affect a territory are just one of many types of interventions available to those in charge of managing the public sector and multilateral agencies, within the overall objective of reducing poverty and promoting economic and social development. To the question of whether it is more important, in a specific city, to invest one million dollars in education or in reducing flood risks, the proposed indices are of little use, since they lack a clear counterpart in other investment axes. There exist generic techniques, most of them economistic, to compare projects of a different nature (refer to chapter 7), but their application requires thoroughly formulating the solution to each problem, and all of them are based on comparing the relative efficiency of a limited set of available solutions, rather than the severity of the problems they address.

Without intending to give a final answer to this issue, many risk assessments, and especially those conducted under ESCI, include some type of practical approach to contextualize in a simple and qualitative manner the diagnosis of risks, so that they can be related to other focal areas. The basic and general procedure that has been applied to develop the so-called “risk filters” is establishing a qualitative, universal and absolute rating scale for risks diagnosis, which is based on abstract categories defined in generic terms, valid for any theme, subject, or sector of interest. There follows an example of a 5-level scale of this type:

Level 1: a highly favorable diagnosis with a positive trend. No significant issues requiring intervention measures are detected for the relevant sector. The condition of the sector does not entail a restriction for growth, but a strength to build upon.

Level 2: a favorable diagnosis with a neutral trend. Emerging issues with a potential increasing trend are detected. The condition of the sector is acceptable and does not limit progress in other areas in the short and medium terms.

Level 3: intermediate diagnosis. There are some moderate issues that require measures in the mid term. The issues detected do not limit progress yet, neither do they have evident systemic effects, but they may certainly worsen over time.

Level 4: an unfavorable diagnosis with a neutral trend. There are some severe issues that require intervention as a matter of priority. The condition of the sector starts to limit growth and to have systemic effects. Their evolution trend is foreseeable negative.

Level 5: a highly unfavorable diagnosis with a negative trend. There are severe problems that require urgent measures. The problems detected represent a clear limitation for growth and have systemic effects, so they need to be addressed as a matter of priority to achieve improvements in other areas.

In terms of risks, the aforesaid levels are equivalent to the typical categories, with their usual color code:

LEVEL 1	VERY LOW RISK
LEVEL 2	LOW RISK
LEVEL 3	MODERATE RISK
LEVEL 4	HIGH RISK
LEVEL 5	VERY HIGH RISK

Table 15 | Generic scale of qualitative risk levels.

Once the situation of a city is reflected in this scale for different sectors, including the risk level, it is possible to roughly establish what are priority intervention themes. While it is evident that reducing the diagnosis of problems to a scale of this type entails a loss of information on the available base studies, such a simplification may be necessary and even convenient when conducting strategic analyses and pre-investment studies in complex spheres of activity, like those of multi-lateral agencies, where thousands of places and tens of thematic lines compete for limited financial and human resources.

To apply a similar filter to that proposed based on the quantitative risk results, it is necessary to establish the expressions that transform the indices (which are continuous variables usually defined between zero and infinite) into a discrete variable within a limited range, from 1 to 5 in this case. The main risk indices presented in chapter 3 can be arranged as follows:

AGGREGATED ECONOMIC LOSS INDICES		
IE1	Total loss index	Total expected annual loss relative to the Gross Domestic Product of a city.
IE2	Buildings loss index	Expected annual loss from direct damage to buildings, relative to the total value of the housing stock of a city.
HUMAN DAMAGE INDICES		
IH1	Fatality index	Average number of annual deaths, relative to the total population.
IH2	Damaged index	Average number of annual damaged people, relative to the total population.
IH3	Affected index	Average number of annual affected people, relative to the total population.
CRITICAL SECTOR DAMAGE INDICES		
CSI1	Proportion of critical elements damaged	Number of critical elements damaged per year, relative to the total number of critical elements, for each sector analyzed.
CSI2	Loss of functionality of the sector	Annual average loss of functionality for each sector, relative to their total capacity.

Table 16 | Summary of the main risk indices used in this Guide.

The definition of the thresholds that determine the level of risk for each index is based on experience and may vary by type of city. In the ESCI, different thresholds have been tentatively used based on a practical knowledge of the region. Table 16 shows the values that have been proposed for the economic loss indices (EI1 and EI2) and the critical sector damage indices (CSI1 and CSI2). As regards human indices, different thresholds are proposed for each index, as shown in Table 17. Given the wide range of boundary values, they are presented as parts per million (ppm), so that a 1% is equivalent to 10,000 ppm.

Both tables have been filled based on expert judgment, assuming that each index varies exponentially with the risk level or, conversely, that levels are proportional to the logarithm of the indices.

Based on the values of the indices and the application of the above tables, a set of risk levels is derived. It is usually convenient to add an upper level to that set of risk levels, assuming that the more restrictive criterion is the one that defines the overall risks level. Thus, in a specific city, it is possible to define an economic risk level (ERL) and a human risk level (HRL) which, combined, result in a total risk level (TRL):

SCENARIO	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
IE1 IE2 CSI1 CSI2	<1 ppm*	1-20 ppm	20-50 ppm	50-100 ppm	>100 ppm

*ppm=parts per million (1% = 10,000 ppm; 1 ‰=1,000 ppm).

Table 17 | Threshold values of the economic loss and damage indices for critical sectors to obtain risk levels.

SCENARIO	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
IH1	<1 ppm*	1-20 ppm	20-50 ppm	50-100 ppm	>100 ppm
IH2	<10 ppm	10-200 ppm	200-500 ppm	500-1,000 ppm	>1,000 ppm
IH3	<100 ppm	100-2,000 ppm	2,000-5,000 ppm	5,000-10,000 ppm	>10,000 ppm

*ppm=parts per million (1% = 10,000 ppm; 1 ‰=1,000 ppm).

Table 18 | Threshold values of the human damage indices to obtain risk levels.

ERL= maximum {IE1, IE2}
HRL= maximum {IH1, IH2, IH3}
TRL= maximum {ERL, HRL}

For each sector analyzed, the aggregated risk level would also be the maximum of CSI1 and CSI2. Another advantage of this classification of risk into semi-quantitative levels is that it has a direct correlation with the perceived risk levels, exactly as they can be derived from public surveys or questionnaires. However, the fact that they share a scale does not guarantee consistency and coherence between both types of results, as they come from very different sources.

6

Risk reduction measures —

6

6.1 Classification of risk reduction measures

Following the general framework presented in the previous chapter, below is an overview of available intervention options to reduce risks in cities. Before detailing and selecting particular measures based on specific conditions, we will present a general and descriptive catalog of all the existing types of available measures – or at least a representative group of them. Said catalog does not intend to be exhaustive or replace the large number of existing documents dealing with the subjects analyzed, it rather seeks to offer a general and non-restrictive overview of the numerous dimensions involved in risk reduction. We have chosen to pay less attention than usual to structural measures, even if they are still the most extended ones and the ones being allocated the largest budgets, because there are highly comprehensive manuals available that fully cover them. Rather, we have attempted to highlight the need for risk reduction programs to be cross-cutting, considering the complexity and dynamism of nowadays cities, especially those with greater growth. Therefore, apart from a brief summary of structural measures, we have included monographic sections on economicist and regulatory measures, emergency prevention systems, and the relation between risks and urban planning.

Aside from the activities seeking to reduce greenhouse gas emissions (climate change mitigation, as per the IPCC language), different classifications can be proposed for risk reduction measures according to the selected guiding principle:

Materiality principle:

- Structural or hard measures: gray infrastructure (dikes, piping, channels, dams, etc.) or green infrastructure (retention areas, green filters, permeable pavement, green roofs, etc.).
- Non-structural or soft measures: regulations, planning, management, communication and awareness-raising.

Principle based on the phases of the risk management cycle:

- Information and prevention measures (prior to a disaster and to the possibility that a disaster occurs).
- Measures linked to the occurrence of a disaster (during the previous instants, during, and on the days following a disaster).
- Measures to strengthen long-term resiliency and recovery after a disaster occurs.

Principle based on competences or on the institutional landscape:

- Municipal activities, classified in turn by local government area: urban planning, sanitation and drainage, mobility, waste, parks and gardens, etc.

- Activities at the regional or national level, often linked to ministry areas: watershed management plans, water and land regulations, energy planning, transportation and communication, etc.
- Activities at the supranational level: border control, international watershed management, supranational meteorological and disaster forecast systems, international cooperation and loans, etc.

The mere existence of these classification systems points at the complexity of the risk reduction problem, the multiple approaches that may be adopted, and the importance of opening a comprehensive and participatory debate to arrive at efficient and long-lasting solutions. While the materiality principle (works v. management measures) is the simplest one, fits naturally in an action-reaction paradigm (problem-solution), and is naturally incorporated to the political discourse and cycle, it does not screen the root causes of the problem, but rather its most superficial elements.

The principle based on the risk cycle is probably the most balanced and the one with the fullest vision, but it is the most difficult to communicate, especially after a tragedy has taken place. Its circular nature (risk management as a continuous process) does not emphasize the symbolism of the struggle against nature. Therefore, this principle is frequently applied in large-scale planning, but may seem hardly appealing at the municipal scale.

Finally, the competence-based principle, which identifies the different players and their weaknesses and strengths rather than the action itself, is probably the most realistic one, but spotlights, right from the beginning, the great difficulties faced by a risk-reduction program, even if only in terms of coordination and institutional capacity. Problems like the lack of knowledge and resources in the institutions, lack of productivity, corruption and overlapping of competences, tend to be risk-generating and/or boosting factors, which are very difficult to change.

The next sections are basically structured following the materiality principle and place the most attention on non-structural measures, without overlooking the risk management cycle and competence-related factors, within each type of measures. As a secondary objective, we have tried to emphasize those issues that have proved to be most relevant or critical in identifying and defining risk-reduction activities within the ESCI.

6.2 Risk reduction infrastructure

From times immemorial, human beings have built large hydraulic works to control the effects of nature, and they may well be expected to continue to do so for many centuries to come. Most countries – especially the most developed ones – have built thousands of kilometers of protection dikes (in rivers, estuaries and coastlines) and a large number of dams for the purpose of reducing floods, among other objectives. All developed and many developing cities have a piping network and pumping systems to remove rain and wastewater that supplement – or even replace – the elements that comprise the natural water cycle.

The criteria for designing and building the different types of hydraulic works have been consolidated in their basic aspects since the end of the 20th century with the mainstreaming of computers and numerical models, the setting of the theoretical bases of all the disciplines involved (fluids mechanics, soil mechanics, coastline engineering, sediment, transport, etc.) and the synthesis of the experience gained during periods of intense development in many countries at different times (United Kingdom, France, U.S.A., China, Spain, South Korea, Israel, etc.).

Such consolidation and convergence of design tools does not relieve technical specialists and practitioners from taking certain decisions for which there is not a single solution and which thus continue to be a subject of debate. The following sections present an overview of some of the issues that keep posing a challenge and difficulties in the design of flood protection infrastructure – especially in LAC urban centers.

Designing with uncertainty in a non-stationary context

One of the first and most important problems faced when designing a risk mitigation measure or program is selecting its level of design, which implies a level of admissible risk. As discussed in section 1.2, the simplest and most extended proceeding is analyzing the probability of occurrence of one or several dominant risk factors – in general, the hydroclimatic hazard variables that generate the greatest impacts or the ones for which more or better historical data is available, like rainfall, wind intensity, sea level rise, etc. From this analysis, an extreme probability function (with one or multiple variables) can be obtained to establish the probability of occurrence of a particular event (usually expressed as a return period in years). Such probability is directly transmitted to the risks/damage associated with said event, and constant values are assumed (without an associated probability) for other hydroclimatic variables which are secondary and for the vulnerability factors involved.

Leaving aside the sources of uncertainty that may be incorporated to this conceptual framework (see section 3.8), a relevant aspect is the implicit hypothesis that the design variables will remain true to their probability function – whose tails (maximum and minimum values) reflect a random behavior which is extreme but nonetheless stable – over time. However, such stability (or stationarity, in statistical language) is altered in a context of climate change, where the basic atmospheric processes are continuously changing, which translates in an evolution of the probability functions of the hydroclimatic variables over time. The study and quantification of such variables is nowadays a highly active research area, but there are still no conclusive criteria when it comes to deciding upon a suitable proceeding for a specific project. As a practical measure, based on regional and local studies available in each city, a disturbance may be incorporated to the parameters of the historical density function of the dominant variable (specifically its mean value and its standard deviation), assuming that its shape (type of distribution) remains unaltered. Another possible approach is to adjust the results obtained from spatially disaggregating (downscaling) the general circulation models available for the area of study. In any case, any modern design project of a hydraulic structure must take into account the problem of the non-stationarity of the design climatic variables.

Optimized data-based system management

It may be said that the history of mankind has already irreversibly entered the era of artificial intelligence and big data. The implications of this for people and, thus, for their main place of residence – the cities – are enormous and often hard to imagine (see a qualified approach to his issue in Harari, 2016). Without considering the – more or less likely – possibility that a hydraulic system (like a dam and its associated reservoir) can manage itself autonomously based on real-time data provided by a network of users and sensors (the Internet of things), it is evident that there is much room for optimizing and improving the operation of this type of infrastructures, even with already existing technologies. It strikes the attention that – in most parts of the world – hydraulic administrations are late in the incorporation of new technologies and use primitive operation methods and criteria (save for the remote control and communication systems – or SCADA, whose use is certainly more or less extended). In LAC, it has been ascertained that clear (and affordable) opportunities exist to reduce hydroclimatic risks in cities by using real-time forecast systems and optimized operation protocols in dams, dikes, and other types of infrastructure (refer to section 6.4).

However, especially in Central America, there are worth noting experiences with the use of new technologies for the issue of real-time alert notices on catastrophic events to the population which often combine different means of communication (radio, TV, mobile telephone, etc.) with networks of volunteers in charge of disseminating the alerts to the population at large. The use of more advanced and accurate technologies, combined with the invaluable social asset of having those citizen networks available to reach communities and neighborhoods, opens the possibility for optimism in countries facing considerable risk mitigation challenges like El Salvador, Honduras, Guatemala, and Nicaragua.

Analysis of the life cycle of infrastructures

All facilities have, apart from execution and commissioning costs, associated maintenance costs (necessary to guarantee their operation throughout their life span) and depreciation costs which economically reflect their obsolescence. Said costs are frequently overlooked in LAC and other places, which results in a loss of functionality and, ultimately, increased risks, even in areas that should be protected. Prior to undertaking the construction of risk reduction infrastructure, it is advisable to clearly inform the relevant entities of the need to make provision for inspection and maintenance works and to make the necessary resources, both economic and organizational, available to perform those works. This is especially necessary in coastal or river levees, whose deterioration in specific places jeopardizes the functionality of the whole infrastructure. In addition, some dams built in LAC in the first half of the 20th century are showing signs of deterioration, creating considerable risks to downstream populations, which need to be assessed and reduced as far as possible. Finally, no work should be undertaken unless a minimum coverage of maintenance and operating costs has been guaranteed (which coverage will depend on the specific work), even if resources for the initial capital expenditure are available. A specific feature of maintenance and operating works is that they not only depend on budget availability, but also require an institutional framework and operating procedures, which are often not up to the task.

Green and adaptable infrastructure

One of the lessons learned over centuries of efforts to reduce the risks arising from natural phenomena is the importance of preserving, or at least imitating, natural mechanisms in the design of interventions. River basins and coastal systems are physiographic units that have evolved with climate over centuries and have developed self-organized and efficient mechanisms of dissipation of matter and energy flows, which can be taken as an inspiration when designing technological systems. This abstract principle is translated into basic design standards which many LAC cities have omitted in their quick and disorderly process of growth over the past decades:

- Areas with smooth topographic slopes are fit for storing water (in lakes, parks, recreational areas, etc.), but do not easily accommodate efficient urban drainage networks, unless costly pumping systems are built and maintained.
- Likewise, it is seldom practical or convenient to store water in areas with steep slopes, since the potential energy stored generates added risks.
- In areas that are subject to seismic and land-slide risks, open-air solutions relying on ductile materials are preferable against rigid walls or underground pipes.
- Cities whose neuralgic points (critical infrastructure) are more scattered and linked with one another will better withstand catastrophes than cities whose strategic assets are concentrated and independent from one another.

Another way of imitating nature is to contemplate multi-functionality, that is, to accept that any element introduced into an evolving complex system, including cities, must operate in multiple situations with different objectives, which are often different from their intended ones at the time they were designed. Sometimes the success of an element or organism lies in its capacity to adapt and operate as a competitive advantage in non-anticipated conditions, rather than fulfilling the specific purpose for which it was designed (for living beings, the one dictated by natural selection). In the evolutionary biologists' language this phenomenon is called exaptation (Gould y Vrba, 1982), and engineers and urban planners may need to get used to designing risk reduction systems that maximize this trait, rather than figure out the design that best meets a number of predefined objectives, in a known context. Therefore, multi-functional infrastructures, which include ecosystem services and recreational-landscaping uses among their potential functions, should be contemplated in the design of the new cities – so that a park, an underground parking area or a sports field may accommodate other functions, in addition to those denoted by their specific names (see Table 11).

A general trait of many green infrastructures or nature-inspired solutions is that the spatial and time scales required for their planning are not compatible with the dynamic pace of some socioeconomic processes. A forest or a marsh require time and space to regenerate, and may also produce deferred effects in both dimensions: a forest improves the hydrological behavior of downstream basins when it turns into a mature forest (after tens of years of growth and ecological successions), and marshes must contribute ecosystem services which extend far beyond their direct physical footprint. Therefore, the assessment and allocation of costs/benefits is more complex than in the direct interactions among entities (whether physical entities or bodies corporate) that consumption capitalism promotes and to which the very political cycle of liberal democracies responds. The vending machine model is not suitable to represent the reality of ecosystem services, nor does it represent a promising approach for the design of resilient risk reduction interventions.

Multi-functional infrastructures, which include ecosystem services and recreational-landscaping uses among their potential functions, should be contemplated in the design of the new cities – so that a park, an underground parking area or a sports field may accommodate other functions, in addition to those denoted by their specific names.

BOX 11

Sustainable drainage systems proposed in Tegucigalpa (Honduras)

Problem

Among the works proposed to reduce flood risks in the city of Tegucigalpa, it was decided to pilot some sustainable drainage systems (SUDS). SUDS refers to a non-limited set of techniques and devices that extend the scheme of a traditional drainage system (based on a mainly hydraulic design of piping networks) to a more holistic conception of urban water management often based on imitating nature, and whose objectives are not only to remove excess water (water as waste), but also the following, among others: improve water quality, landscape and urban improvement objectives, environmental improvement, production of supply water, etc.

Methodology

Three multiple-target works were proposed whose main objectives were:

- To reduce flood risks due to extreme rain events in Comayagüela and the historical center of Tegucigalpa.
- To create sports equipment and public spaces for people to gather and interact within the urban area.

As a secondary objective there was the improvement of the quality of runoff water (whether poured into a course of water or moved to a treatment plant) and, if it was decided to bury part of the storage volume (floodwater storage tank), water supply for non-consumptive uses.
The basic design of the three proposed systems focused on simultaneously meeting the two main objectives, while the verification of the degree of fulfillment of the secondary objectives was left for a more advanced phase of definition of works. Therefore, the two design criteria incorporated into this work phase were as follows:

- To guarantee that the proposed systems collect the whole of the runoff produced in catchment areas for a 10-year event.
- To create a sports or public use area of at least 30 x 40 m fitted with a grandstand to accommodate 100 people, which would also serve as a floodwater retention pool.

Result

Two areas were selected in Comayagüela (see Figure 37), and several sustainable drainage systems with similar characteristics and components were proposed to be built in those areas:

1. **Drainage ditch:** An intercepting sewer functioning in a free nappe that collects runoff water from the catchment area, filters it and moves it (if possible, already filtered) to a storage pool (sports field) (Figure 38 above).
2. **Sports premises with an alternative function as an open-air storage area:** An open-air storage pool which also serves as a sports field, which stores water coming from the sewer and that is fitted with a deep outlet and a surface spillway (Figure 38 below).

3. **Pressure pipe:** An iron pressure conduit that starts in the deep outlet of the pool and ends in a lower point, whether in the Choluteca river or in a sewer of the combined sanitation network.

Finally, a third intervention area was designed in the historical center of Tegucigalpa with a similar operating scheme (intercepting sewer and pressure pipe), but without a storage tank.

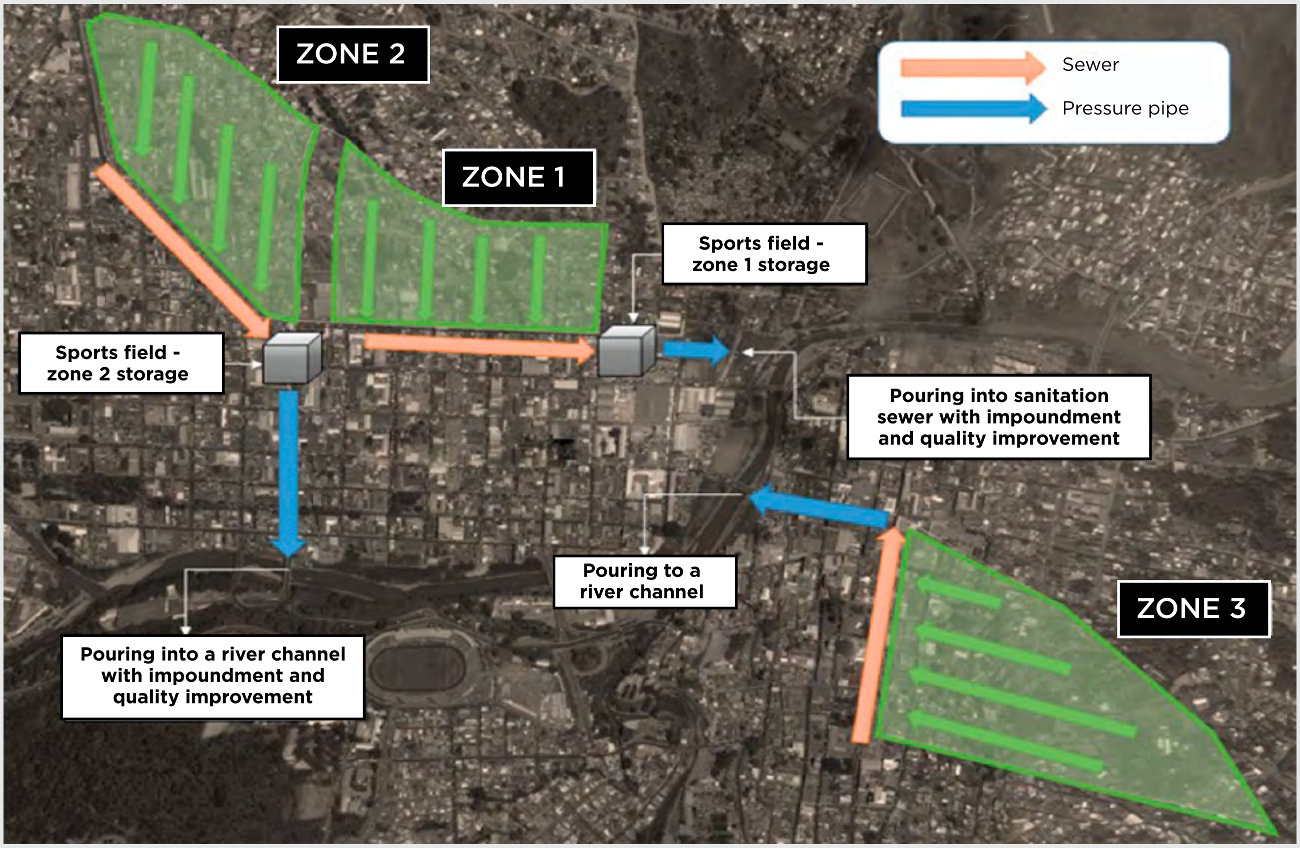


Figure 37 | Location and sketch of the three intervention areas.

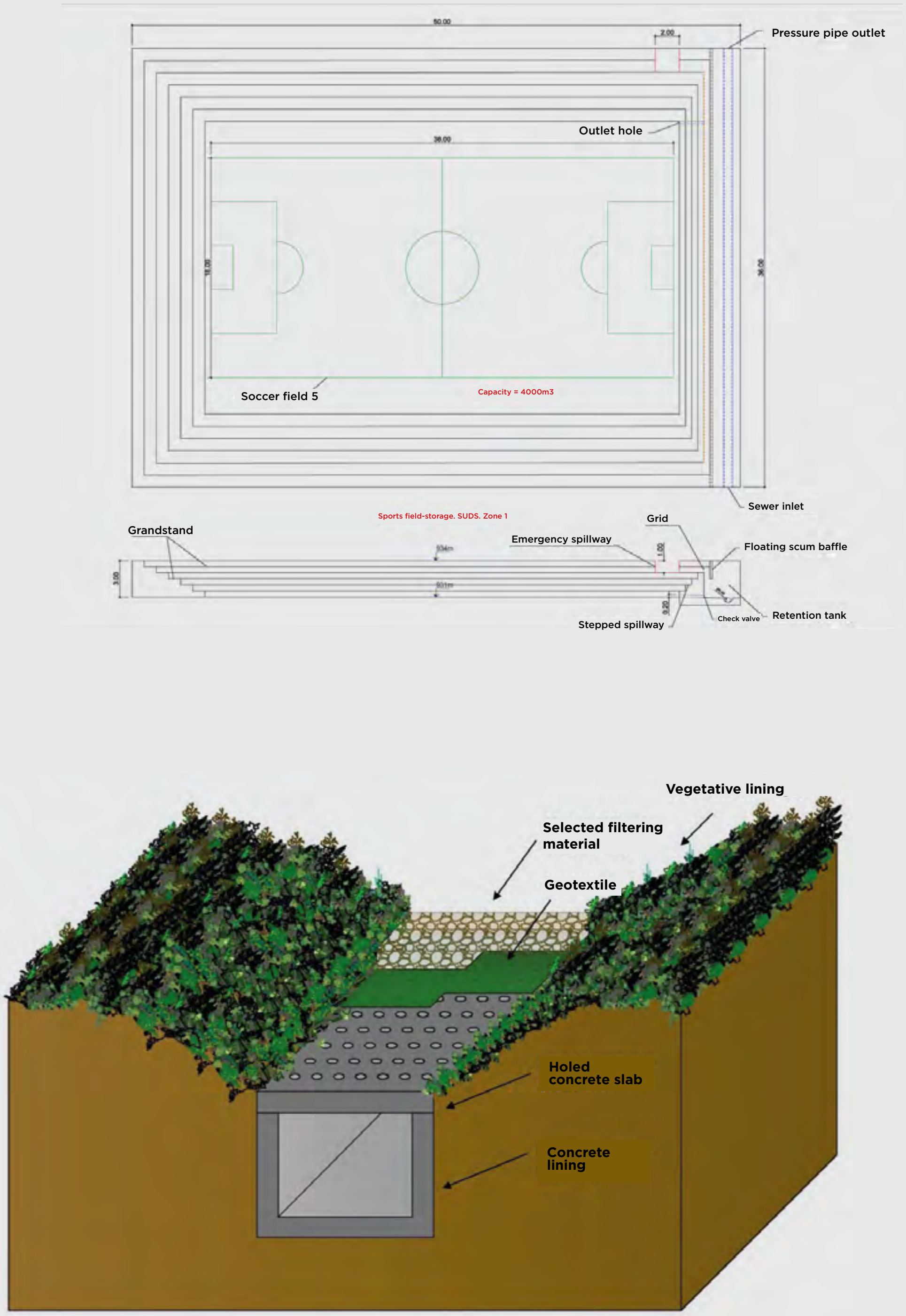


Figure 38 | Above) Detail of sports field-storage area. Zone 1. Below) Standard section of the drainage ditch.

6.3 Land planning and urban metabolism from a risk perspective

A significant portion of urban risks is associated with an unsuitable location of uses and people. In many cases, the growth of the urban patch has not followed an urbanism or land planning logic, especially in LAC cities that have experienced periods of heavy expansion in the last decades. Even when it did follow an orderly scheme, planners have not always had access to risk diagnoses and have thus not been able to incorporate this information into development master plans.

The experience with the ESCI confirms that the territory where cities are located is not a homogeneous entity, as each area is fit for specific uses depending on its physical features (soil, slope, climate factors) and has its own mechanisms of interaction with its neighboring territories. Consequently, whenever a use is assigned to a given area, not only the fitness of the area for such use is put to the test, but also the fitness conditions of other related territories are modified. When a new area is built within a city, it is not only necessary to test its characteristics from a local viewpoint, but also to consider the risks that are being exported (or imported) to (or from) other neighboring areas.

Traditional urban planning (with its regulatory and predominantly static approach) is in a position to understand the risks associated with each area, and therefore limit its uses, but finds it difficult to consider systemic and dynamic effects. Therefore, the building works done in the periurban slopes of some cities located in concave valleys have recently created a risk of flooding that affects ancient historic centers which had never experienced this phenomenon before. The newly occupied areas are not a priori unfit by themselves (except for steep slopes at landslide risk), but because of the risks that they generate for other areas, which are sometimes distant.

This example is useful to trigger a general reflection: land management plans for cities, especially in LAC, are useful and suitable, but not sufficient to guarantee sustainable growth and appropriate urban risk management.

There follows a brief description of some aspects that need to be addressed in order to supplement and improve traditional urban planning methods.

Boosting a dynamic approach and planning as a process

In many cities, the approval of land management plans, whether new or revised, follows a long and winding path that involves struggles for power and conflicting interests. In the meantime, cities continue expanding in an organic manner at their natural pace and, by the time a new plan gets approved, the starting conditions have changed and the plan is no longer strictly valid. At best, urban planning is out of pace with urban development in the fastest growing cities; at worst, urban planning legitimates, with a rational veil, a reality that happens without following any logics other than the enrichment of a few individuals. In face of these circumstances, the models for decision-making on the urban space need to have shorter time frames and to be more flexible, trading off part of the alleged rigorousness and accuracy of traditional plans for a greater dose of pragmatism and possibilism.

Incorporating baseline risk information in urban planning

Many cities do not have detailed and reliable information on the risks affecting their territory, let alone on their potential to export risks. In other cases, they do have information, but it is sector-specific and disconnected from the planning agencies. It is

Figure 39 | Informal settlements in the coastal park of Laguna de los Patos, Cumana, Venezuela convenient to build links between the risk and land management departments, as well as promote a risk culture among them, especially in those cities that face more problems.

Scales of planning and coordination with neighboring municipalities

Sometimes urban planning does not stem from a land use act at the national level, so there is no guarantee of coordination among neighboring municipalities and different land planning scales (national, regional and local). As a result of this, the aggregation of plans from different municipalities shows inconsistencies or even discrepancies on a regional or national scale (for instance, it is common to see local population growth projections that are inconsistent with those same projections on a national scale). It is also common to see a municipality's development plan transferring risks to neighboring areas. The arbitrary division between municipalities, often within one same metropolitan area, with borders that lack any physiographic logic, may (and usually does) encourage an improper use of land.

Strengthening the land management system

In addition, as supplementary to a land use act, it is necessary for the cadastral system and the real estate registry at the national level to be well developed. The agencies involved should have the required capacity (on a city level) and adequate resources to perform their functions. The role of such agencies is also key to the proper operation of the land and real-estate markets. A critical issue is the regularization of the areas with informal settlements, which are often the areas most exposed to hydrometeorological risks.

Advocating for the land markets to reflect and incorporate risk aspects

Land markets are complex, but it is often the governments and local administrations themselves that make them even more imperfect by introducing regulations and subsidies that prevent prices from reflecting reality, including latent risks. This dissuades companies and individuals from spending on risk reduction by selecting more appropriate lands or building according to stricter regulations. It is important that the price of land and properties be commensurate with the risks they are exposed to and that this variable does not operate as an externality.

Training of technical staff

It is necessary to invest more funds in training the technical staff of municipalities and other agencies in the field of sustainable urbanism and risk. Base studies for land management plans, as well as risk studies, are often drawn up by international consulting firms, with little actual participation of local specialists. While outsourcing services is somewhat necessary given the scant resources usually available at municipalities, the opportunity to build local experts' capacities and to provide them with tools should not be missed whenever a work of this type is subcontracted.

In addition to urban planning aspects, there are other aspects of municipal management that are closely related to risks, and that are discussed in the following sections.

Urban mobility and natural catastrophes

The road, highway, bridge, and transportation infrastructure networks in a city greatly influence the damage and response in the event of catastrophes. In the first place, a city whose main roads are often impacted experiences indirect economic costs from longer travel times, which are sometimes considerable (see Box 12). In addition, the efficiency of evacuation and rescue activities in an emergency is related to the resiliency of the transportation network – when it is greatly affected, rescue times and fatality rates increase.

Urban solid waste management and its relationship with risks

Many cities in LAC have a deficient waste collection and management system, especially in certain low-income neighborhoods, which are often located in critical areas like riverbanks and unstable slopes (Figure 40). This poses severe risks to the health of the people living in these areas, and also results in siltation and clogging of drainage lines, especially in storm and wastewater sewers, which are not prepared to receive large amounts of solid waste. Many LAC cities have their urban drainage sewer inlets clogged due to the accumulation of debris and waste that are dumped to the ditch or at irregular dump sites. In addition, since these materials are washed away by runoff waters, they add a significant load of pollutants to the water, which ultimately flows into aquifers, rivers and coasts, generating potential impacts on fisheries, aquaculture, bathing water, water supply systems, etc.

Consequently, solid waste management has a clear impact on health and flood risks in many cities, and any attempt to build urban drainage networks will be unsuccessful if this problem is not addressed as a matter of priority. Adding grates to the inlets of sewer and drainage pipes solves part of the problem, but if regular cleaning is not done, they will also end up being clogged.

Urban water, energy and communication networks as resiliency factors

The metabolism of cities is based on close networks that convey water, energy, and information. Although those networks are scarcely visible, their resistance and capacity to recover in case of a disaster are key to minimize the possibility of complete damage. Keeping the drinking water system operating after a catastrophe is one of the factors that enables minimizing indirect damage and contributes to the population survival in the short and medium term. In addition, a fast recovery of the power system greatly facilitates evacuation and rescue activities during the night and reduces potential vandalism that may derive from a lack of lighting and failures in alarm systems. Finally, the communication networks (especially the mobile telephone network) help issue timely alerts and provide quick assistance in an emergency – which was unthinkable until recent times.

All of the aforesaid facts emphasize the importance, from a risk management viewpoint, of integrated urban planning including not only the planning and risk departments, but also many other areas that are often ignored when it comes to dealing with these issues.

Landscape authorities as new critical players in risk management

Most of the municipalities of a certain scale have a landscape department whose main mission is to design and maintain parks, yards, and other urban spaces for public use. Following the new trends in urban runoff management, the recreational and ornamental function of parks and sports facilities should be coupled with risk reduction and environmental enhancement. Green (and sometimes gray) urban spaces embody the greatest opportunity for cities to promote sustainable and resilient water management.

In order to effectively incorporate these functions in landscape departments, great efforts involving people training, budget allocation, and coordination with other departments are required. Sometimes simple adjustments to the design of parks and bandstands can bring visible urban benefits (for instance, if adjustments are made to prevent them from expelling water outside instead of collecting it). If the land allocated for green areas is not spared and green areas are designed to perform other functions apart from purely ornamental ones, landscapers will play an increasingly important role in the cities of the future.

Figure 40 | Dragging of sediments and waste in Hoyo de Puchula (above) and Hoyo de Bartola (below) in Santiago de los Caballeros (Dominican Republic).

Figure 41 | Accumulation of waste in Los Molinos and Llanada channels in Cumana (Venezuela).

BOX 12

cost of traffic interruptions due to flood events in Tegucigalpa (Honduras)

Problem

As part of the cost-benefit analysis conducted for the city of Tegucigalpa (see Box 14), a potentially important result of the new flood control works being designed would be to prevent traffic congestions derived from interruptions in the operation of the bridges that cross the Choluteca river as well as its main tributaries in the central area of Tegucigalpa.

Methodology

As baseline information, there is the Supporting Study of the Sustainable Urban Mobility Plan (PMUS, by its Spanish acronym) for the Central District of Tegucigalpa and Comayagüela (Final Report, IDB, December 2012). Nine bridges have been considered to be representative of the total traffic. Their peak traffic intensity (adding their traffic in both directions) is 5,000 vehicles/hour, and it will be assumed that within that time window the mean intensity is roughly a half of the peak intensity, that is, 2,500 vehicles/hour.

Assuming that a riverine flood with a return period of more than 10 years generates a traffic interruption of 8 hours, then such flood would affect about 22,500 vehicles (if occurring during daytime on a business day). This figure represents, according to the aforesaid Mobility Plan, about one third of all the trips that occur on average in one day in the city and almost a half of those made with a four-wheel vehicle.

Based on information provided by local residents, it has been also estimated that when the bridges are operational it takes two hours on average to bypass the city and reach the point of destination through other roads. If we consider that the average cost per hour used to bypass the city is equivalent to an average wage cost, and consider an average wage of two times the minimum wage approved by law in Honduras (USD 400 per month in 2015), the result is an hourly cost of delay of 5 USD.

Result

If we combine all of the aforesaid figures, we get an average annual cost of traffic interruption of USD 180,000:

HOURLY COST OF INTERRUPTION*	5	USD/hora
LENGTH OF INTERRUPTION	8	hours
AVERAGE TRAFFIC INTENSITY BY BRIDGE	2,500	Vehicle/hour
NUMBER OF BRIDGES	9	-
ADDITIONAL TRAVEL TIME	22,500	Vehicle/hour
TOTAL COST OF DELAY PER EVENT	2	hours
TIEMPO ADICIONAL DE VIAJE	1,800,000	USD
AVERAGE RECURRENCE PERIOD OF THE INTERRUPTIONS	10	years
ANNUALIZED DAMAGE	**180,000**	**USD/year**

Table 19 | Costs of traffic interruption.

6.4 Early warning systems and emergency management

Based on the knowledge of natural processes available nowadays, combined with information and communication technologies, it is possible to predict many hydroclimatic, geological, epidemiological and other types of phenomena with certain anticipation. The information provided by early warning systems may be integrated in systems for issuing notices to the population, which in turn may be tailored based on the location and specific characteristics of the risk event. Finally, a predictable and coordinated behavior of the population may facilitate the evacuation and safeguarding activities targeted at both assets and people, which will ultimately reduce damage drastically.

Unlike the measures discussed in previous sections, this sequence of processes requires integrating technological, institutional and human behavior aspects in a very tight time frame, where important decisions need to be taken quickly and under straining conditions. There follows a description of the main aspects that need to be considered when designing the different components of an early warning system.

Risk forecasting and issuing of alerts to the authorities

This is the most technical component of an early warning system, although more advanced technologies are getting increasingly used in the other tasks involved (e.g., massively sending personalized messages to the exposed population). Risk forecasting basically involves continuously and regularly following a procedure that is similar to the one described in chapter 3, which depends on the type of risk:

1. Receiving real-time data on the variables that control the hazard, which, for hydroclimatic risks, implies combining synoptic or mesoscale meteorological models with local sensing devices like coastal buoys, rain gages, water-level gages, etc.

2. Converting the forecasting of the hazard source variable into the derived variable that determines risk (e.g., the transformation of rain into river levels in a given area or the transformation of a tsunami from the point where it is generated to the coast). This conversion often requires numerical models that require prior calibration and validation.

3. Risk forecasting and issuing of alerts to the authorities. Finally, the forecasting of a hazard may be transformed into expected damage, following procedures as those described in chapter 3. Based on the damage forecast, including, if possible, the associated uncertainty, it is possible to establish levels of alert to notify the situation to the authorities.

Activation of emergency protocols

The previous activities do not yet involve decisions that affect the community, which should be taken by the relevant government authorities, usually gathered as cross-sectoral committees for emergency management. Based on the level of alert generated by technological forecasting systems, the relevant emergency protocols specifying the measures to be taken need to be activated. Measures may range from communication activities to a massive evacuation and preparation of places to accommodate refugees, as well as the closure of roads, safeguarding of critical elements, requesting national or international assistance, etc.

It should be noted that the economic cost (let alone the human, political and other types of costs) of issuing a public alert is high and is largely borne by the population itself. This puts considerable strain on those in charge of activating protocols, who will want to understand what is the uncertainty associated with the technological system whereupon they base their decisions, which is characterized by two types of failures:

- Probability of issuing warnings about risks that do not actually materialize (false positives). This type of error generates low economic costs (compared with those of a catastrophe), but due to its costs being largely borne by the population and to its repercussion on the media, political costs are often high. On top of this, there is a deterioration in the credibility of the system, which affects the response of the population in future events (see next section on the social component of warning systems).

- Probability of underestimating or not detecting extreme events (false negatives). This failure is undoubtedly the one that carries the greatest economic costs, but it may paradoxically involve lower political costs. In addition, user credibility with respect to the warning system gets less damaged.

All in all, when it comes to early warning systems, the quantification and reduction of the uncertainty associated with forecasts is key for decision-making purposes. To reduce forecasts uncertainty, it is important to consider a combination of measures, including the deployment of a closer or better-resolution network of sensing devices, ad hoc calibration and, where possible, underlying process models with ongoing self-learning capacity, apart from frequent updating of the vulnerability factors that determine risks (use and population layers).

Preparedness and population response

The two previous steps that embody the technological and institutional components of a warning system will fail to completely attain their objectives of reducing risks if they are not supported by a third component which is social in nature. Once warning notices have been issued and a decision has been made as to the relevant steps to be taken, it is the people and their behavior in extraordinary situations that have the final say in terms of risks – for which they have often not been prepared either physically or mentally. People's confidence in institutions, local idiosyncrasy, and the history of successes or false alarms of the warning system are some of the factors that lead the population to obey instructions in an emergency, or to otherwise decide to act based on their own (individual or group) criteria. In any case, it cannot be assumed that the population will respond appropriately in an emergency, and this is ultimately an important issue that needs to be preventively addressed in the long term through the implementation of disaster preparedness and education tools.

In the past few years, thanks to the population's general access to mobile devices and the boom of social networks, remarkable progress has been made in launching risk alert messages that are tailored according to the type of disaster, user location and profile, etc. Technology and the capacity to process and interpret large amounts of real-time spatial data will undoubtedly lead to advances in the reduction of risks associated with catastrophic events. However, as it happens whenever psychological and sociological factors are present, complexity and unpredictability will continue to be inherent features of any emergency management system.

7

Alternatives assessment and selection techniques —

7

7.1 General framework for the assessment and selection of alternatives

Section 6 presented a set of measures of different nature to reduce hydroclimatic risks in the cities in the form of a general guiding catalog. This section will focus on presenting and describing different procedures to select the most suitable alternative considering multiple criteria and indicators. The proposed techniques and procedures will a priori be useful to compare both individual and sets of measures, and even complete sectoral plans or programs. The general method for selecting a program of measures to reduce a given type of risk may be divided in three main phases of work:

1. **Identification of basic viable strategies and associated programs of measures**. Given a city with its specific issues, it is neither advisable, nor feasible to consider the whole of the alternatives described in the previous section as viable options that should be compared; rather, there is an intermediate step that can be followed to discard a number of actions based on local conditions and experiences. This initial screening and short listing of candidate options for the selection process does not follow a predefined method; it is rather the result of a holistic assessment of the available information.

2. **Analysis, basic sizing and preliminary assessment of measures** associated with each of the strategies considered. It is not possible to compare and assess the shortlisted options without characterizing their essential features with a certain degree of detail: main dimensions (in the case of structures or equipment), critical relations among the measures, expected effects (degree of risk mitigation and residual risk), estimated budget, term, etc.

3. **Systematic evaluation and comparison of the selected programs of measures**. With the information obtained in the previous phase, different formal procedures may be followed for the analysis and selection of alternatives. First, a selection method should be picked weighing the advantages and disadvantages of each, as described in further detail in the following sections.

The effort associated with the first two phases is often ignored or minimized, and attention is mostly placed on the techniques for comparing alternatives, which are usually more standardized. However, the validity and quality of the results of the last work phase depend on the previous phases, so it is advisable to address them with the same level of accuracy, as parts of one single process.

The first step in establishing a course of action aimed at reducing risks in a city involves defining the potential action strategy(ies) based on a diagnosis that reflects the real conditions in the city being studied, considering all aspects (refer to section 5) and, especially, the risk construction mechanisms that have historically operated. The action strategy must precede any program of measures and, most certainly, any specific risk reduction effort included in a specific program. The strategies should define assumptions and general basic objectives that set the limits of what is feasible to do and what can be expected in terms of reducing hydroclimatic risks in a city. The strategy must formulate the risk reduction objective, which in no case can be the complete removal of risks, and the relation of forces between the potential approaches that can be used to accomplish it: technology versus naturalness, works versus panning and management measures, adaptation versus mitigation, etc. Following a debate involving the main social players, a consensus should be reached on a suitable risk reduction strategy for each specific case; in some cities, an agreement may not be reached and multiple candidate strategies may result, which will afterwards be compared.

Each of the defined strategies will be coupled with one or two programs of measures comprising a set of specific coordinated measures aimed at materializing the strategy (see Box 13). Sometimes a strategy will be clearly associated with a package of activities, while in other cases there will be multiple alternatives to meet the objectives within a predefined framework. In any case, the programs of measures associated with one or multiple strategies must be broken down in specific actions which should be individually characterized in material terms (dimensions, necessary premises), in terms of impacts (expected positive and negative results), costs, deadlines, etc. The preselected and characterized packages of measures, either for one single strategy or for multiple strategies, will move on to the final procedure of analysis of alternatives.

The systematic evaluation and comparison of alternatives may be addressed from a purely quantitative or qualitative perspective, or from a combination of both. The quantitative and semiquantitative methods are based in the maximization (or minimization) of a target function, whose nature and specific characteristics are part of the decision making process. The most common types of target functions are the following:

- **Functions based on financial profitability parameters:** the properties (positive and negative factors) of each alternative are translated into monetary flows distributed over time, of which profitability parameters can be derived, like the net present value. Thus, all the alternatives are translated into a unidimensional scale, so they can be ranked according to their efficiency. This is the classic cost-benefit or cost-effectiveness analysis, which is described in greater detail in section 7.2.

- **Semi-quantitative ratings weighing functions:** they are based on building a function that, by allocating different weights, combines different aspects of an alternative expressed through semi-quantitative scales (from 1 to 5, for instance). The ratings for the different aspects of each alternative often result from aggregating the judgments of a group of experts. This approach is generically called multi-criteria analysis and, since there is interaction and feedback among the experts involved, it is similar to the Delphi methods (section 7.3).

Finally, the qualitative methods assume and preserve the multidimensional – and often incommensurate – nature of the factors that determine the advantage of a package of risk reduction measures. In these methods, communication and debate become basic tools to build bridges between the different parties in order for them to reach a consensus that satisfies the majority of them.

In general, the qualitative approach – often framed within public engagement processes – is used during the first planning phase, where an overall strategy to solve the problem is defined. In the following phases, where measures are addressed more concretely, cost-benefit analyses and multi-criteria quantitative techniques are often preferred. The expert panels and the Delphi method are flexible tools and more expensive to implement, so they are a priori valid for all decision making phases, depending on how they are designed in each specific case.

Contrary to general perception, the quantitative and semi-quantitative methods do not solve the problem of subjectivity more efficiently than other softer techniques based on communication efforts, but put it on the background. Therefore, when in a cost-benefit analysis an economic value is assigned to human life or to an ecosystem, or through multi-criteria methods relative weights are assigned to environmental factors versus economic factors, what is being done is simplify the underlying problem following a technocratic paradigm.

The following sections will describe with a certain degree of detail two specific techniques for the selection of alternatives highlighting how they should be applied to risk reduction in the context of cities. The focus will be placed on the more quantitative methods (cost-benefit analysis and multi-criteria techniques) which implicitly support a notion of planning as a linear, ruled and predominantly deterministic process.

BOX 13 —

Alternatives for reducing flood risk in the Belize City (Belize)

Problem

Belize City is a coastal city located at the mouth of the Belize river that is exposed to three types of floods:

- **Pluvial flood:** Rain events of a high intensity and short duration that result in a rapid saturation of the drainage system, which generate flood elevations of about 30 cm in many areas of the city several times a year, causing severe disturbances to the population.

- **Riverine flood:** Overflow of the Belize watershed due to prolonged rainfall and/or extreme rain events frequently associated with hurricanes or tropical storms.

- **Coastal flood:** Storm surge caused by tropical storms, hurricane winds and low pressure systems that reach the coast. The city is within the hurricane belt of the Caribbean and, on average, is affected by one hurricane every 3 years.

As a result of this, the city has suffered severe economic and human damage, and the situation is likely to worsen due to the sea level rise produced by climate change, and demographic growth in the city.

Methodology

As regards risk reduction measures, there are two different strategies for defense against floods in this type of cities (sited in low and shallow areas that are exposed to the coast): to either dredge large channels to increase the drainage capacity and the amount of water that can be stored, or build a temporal polder (to isolate the city trough perimeter dikes and gates to separate the inner from the outer water regime).

For a long time, the defense against floods in the city of Belize has relied on several large channels. Most of the areas that lie above the sea level have been largely built from the dredging of channels and the filling of mangroves for many years. It is worth noting that the urbanized area has considerably increased in the past decades and some ancient channels have been turned from gentle-slope channels into straight concrete channels to create vehicle parking areas, and many others have been buried or covered. The inability to generate sufficient channel capacity due to a lack of space, combined with the sea level rise, have rendered the channel-based flood defense strategy unfit for the city. Therefore, the only alternative to reduce future flood risks in Belize is to move from a channel-based strategy to a strategy based on pumping systems. This involves a shift of paradigm in relation to the current situation, which will require a number of structural and non-structural risk reduction measures and a new disaster risk management philosophy.

Results

To achieve this new paradigm 4 risk management programs have been proposed. The first three are related to the three types of flood risk (riverine, urban, and coastal), and the fourth is a cross-cutting program based on the capacity to manage flood risks according to the new paradigm.

1. Riverine flood risk management program

This program focuses on controlling and mitigating the effects of riverine floods by deviating the Belize river before it reaches the city, and it comprises two actions:

- Deviating the Belize river: This work includes three different interventions, the deviation works, which include a spillway to control the inflow of water into the city, and the dredging and stabilization of two areas that will form an alternative river course up to the river mouth in the mangrove area.
- Inner perimeter embankment: Essential work to prevent deviated water from re-entering the city. This inner wall is the first step to build a polder-type protection in the city (in extreme situations).

2. Pluvial flood risk management program

This program focuses on controlling and mitigating the effects of pluvial flood in the urban center of the city. To this end, the three areas that are most affected by this type of floods have been selected, and it has been proposed to establish pumping stations to drain the water accumulated in each pluvial flood event to the sea. The idea is to connect the low areas through a network of channels and remove the water from those areas.

3. Coastal flood risk management program

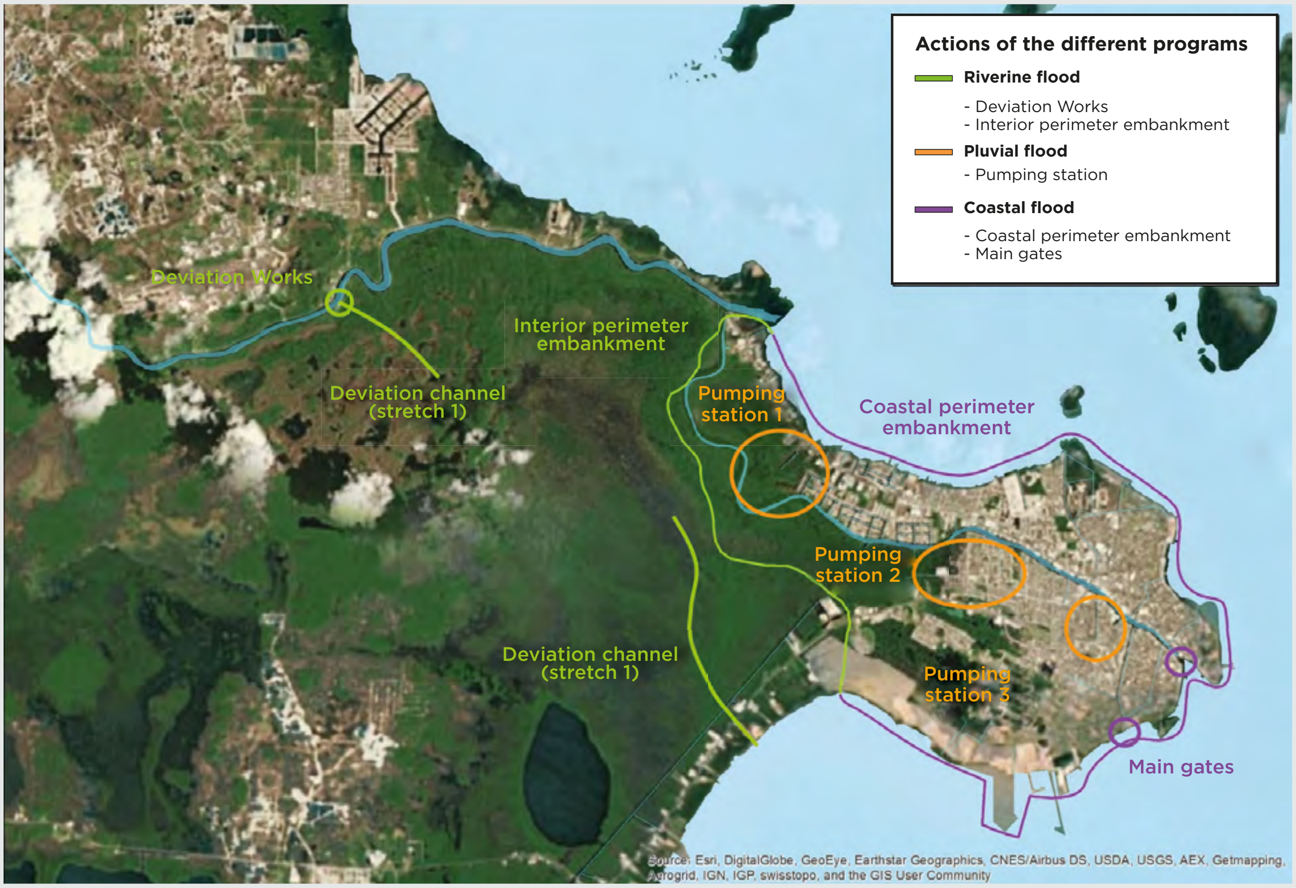
This program focuses on controlling and mitigating coastal flood risk; it attempts to prevent the entry of sea water and to prepare the city to endure a storm surge with a 10 to 20-year return period (1.5 m above the current average sea level). If the sea level exceeds this threshold, in the event of a huge hurricane, the proposed measures will not be effective and non-structural measures will have to be adopted (evacuation plan). This program comprises two actions:

- Coastal perimeter embankment: This wall, together with the interior wall, will protect the urban area from a sea level rise associated with tropical cyclones and hurricanes.
- Gates: They will be fitted in all the outlets of the existing channels to prevent the entry of water during flood events.

4. Capacity building and non-structural measures program

The aim of this program is to strengthen risk management capacity within this new strategy for defense against floods based on a polder. Its actions include:

- Institutional strengthening, including the provision of the equipment required in an emergency.
- Review and improvement of the local emergency plan.
- Training on implementation and coordination to key stakeholders like mayors, firefighters, hospitals, police departments, and schools.
- Community strengthening for risk management and preparedness.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 42 | Location of the actions proposed under each program.

The first step in establishing a course of action aimed at reducing risks in a city involves defining the potential action strategy(ies) based on a diagnosis that reflects the real conditions in the city being studied, considering all aspects and, especially, the risk construction mechanisms that have historically operated.

7.2 Cost-benefit analysis of risk reduction measures

The cost-benefit analysis (CBA) is a quantitative method for the analysis and selection of alternatives in general, and risk reduction measure programs in particular, based on evaluating their cost effectiveness, represented by some financial profitability parameter; it is basically a balance of benefits and added costs that introduces a temporal preference factor and assigns more weight to present versus future cash flows. The CBA techniques are suitable tools to rank a set of options for solving a problem or dilemma, as long as their advantages and shortcomings can be monetized – i.e. they can be assigned a price in monetary units to convert them in benefits or costs. Where the alternatives under analysis only include conventional market goods, the current prices are directly incorporated and it is there that the CBA is based on firmer ground, although there will always be sources of uncertainty (e.g., the evolution of supply and demand, in the context of a competitive market dynamics). This is the case with corporate decisions in a micro-economic context, where any business analysis is ultimately a cost-benefit analysis; here, the discount rates are equivalent to the cost of capital in the financial markets.

The use of CBA in the evaluation of public policies is common practice, although it has some specific characteristics that are worth noting:

- Determining the applicable discount rates in projects related to public policies is a more controversial task than in the case of a company or an individual.

- Many of the – positive or negative – effects of the implementation of a public policy are of a social, environmental, or even cultural nature, so they are difficult to rate in monetary terms.

- Even the strictly economic costs and benefits derived from the implementation of a specific public policy are difficult to assess in all of their dimensions (concealed and indirect costs and benefits, the so-called externalities), due to either a lack of information or the unpredictability associated with the system supporting them.

- Constant discount rates, based on the compound interest formula, suffer an exponential decline over time, making long-term cash flows almost vanish. In terms of public policies, this implies an inter-generational bias and leads to a misrepresentation of projects whose benefits or costs are distant in time.

- The cost-benefit analysis does not consider the way in which the cash flows are distributed among receptors and, therefore, overlooks the social equity and equality aspects. This omission is particularly relevant when analyzing investments in developing countries, where the distribution aspects are often considered a priority.

When it comes to the assessment of public policies and investments, the application of the CBA to the assessment of risk reduction measures reveals even more specific challenges and limitations, in addition to those already mentioned. In general, a CBA applied to a risk reduction effort should consider the following cash flows:

- Fixed costs of infrastructure and technological systems.

- Relocation and compensation costs (may be included in the works budget).

- Variable maintenance and operating costs associated with infrastructures and systems.

- Direct economic damage to buildings.
- Direct economic damage to critical infrastructures.
- Damage to individuals that can be monetized (e.g., refugee shelter costs).
- Indirect damage from traffic alterations.
- Indirect damage from business interruption (loss of profit).
- Benefits from the generation of land value surpluses derived from the planned measures.
- Social benefits from job creation and local consumption (usually associated with building works).
- Other indirect benefits or damage (tourism, citizenship safety, public health, etc.).

As can be observed, most cash flows are negative (costs or expenses) due to the risk reduction efforts essentially being defensive measures that attempt to reduce the damage that would occur if no effort was done at all (zero alternative), usually without intending to generate net benefits (for that, land value surpluses and the rest of indirect benefits should exceed the sum of all investments and operating costs). However, in CBAs applied to this type of projects, it is common practice to consider the zero alternative as a baseline and treat as benefits (with a positive sign) the damage reductions that each alternative measure generates as compared to the zero alternative. With this convention, the zero alternative does not generate cash flows and its net present value (NPV, see definition below) is zero, which means it is not necessary to analyze it, which in turn facilitates the interpretation of the results of the other alternatives (any alternative with a NPV higher than zero is better than the zero alternative).

Other than that, the profitability parameters used in risk reduction projects, which are useful to compare alternatives, are the same as those used in other fields:

- Net present value. It is the sum of all discounted cash flows (that is, expressed in constant monetary units for a given year, which may be the project's start or end year).
- Standard internal rate of return (IRR) and modified internal rate of return (MIRR). It is the discount rate that equals discounted costs and benefits (NPV=0) and gives an idea of the internal profitability of the investment.
- Payback period. Time necessary to reach a financial equilibrium (time when the sum of discounted expenses is equal to the sum of discounted income).
- Cost/benefit ratio. The quotient between the sum of both concepts, previously discounted.

For a detailed description of these concepts and other aspects of the application of CBA techniques, refer to any of the multiple manuals available on this subject (de Rus Mendoza 2004; Sullivan, Wicks, and Luxhoj 2004; Bierman Jr. and Smidt 2012). The following sections contain a summarized overview of certain specific features of the CBA applied to risk reduction measures with the objective of presenting some recommendations and lessons learned from the experience with the ESCI. Box 14 shows an example of the application of CBA techniques in a risk reduction intervention.

BOX 14 —

Cost-benefit analysis of flood control alternatives for the Choluteca river in Tegucigalpa (Honduras)

Problem

The flooding of the city center and metropolitan area of Tegucigalpa is one of the natural risks that most significantly affects the future sustainable development of this city. The root cause of this problem must be sought in its own disorderly growth, which has been curtailing the hydraulic capacity of the rivers and creeks that run across the city to levels that currently make it dangerous to occupy some urban areas that are close to them. Among these courses is the Choluteca river, which is the main river, and a set of minor streams and creeks.

Methodology

A cost-benefit analysis has been conducted to determine the economic viability of a number of structural works proposed to adapt the channel of the Choluteca river, designed for a 50-year return period.

An influence area of such works has been defined to appropriately estimate their effects. This aspect is especially relevant in order to assign to each work the effects expected from their implementation.

The cost of the investment associated with such works has been calculated considering the following:

- The flood control works, discounting the project budget items intended for urban improvement (revegetation of annexed areas, riverfront walk, etc.).
- Maintenance and operating costs: 1% of the investment amount.
- All works have a 3-year building period and a life span of more than 50 years.

These costs are offset by the following types of benefits, understood in the first three cases as a cost saving in relation to the scenario without interventions:

- **Damage repair savings:** It is obtained by subtracting the yearly average damage related to the no-intervention scenario from the yearly average damage related to the intervention scenario.
- **Reduced impact on traffic on high-water days:** It results from the avoided traffic congestions caused by the non-operation of the multiple bridges that cross both the Choluteca river and its main tributaries.
- **Reduction of direct and indirect damage to the markets near the river:** It is determined by calculating the annual average damage (both direct damage and loss of profit) that the flood control works would prevent.
- **The investment budget is reversed to the local community:** Based on the experience of IDB with other similar projects, it has been considered that 15% of the works budget translates into a social benefit channeled to the local people through direct and indirect job creation.

Results

The economic assessment of the investment related to the works for building a new section for the Choluteca river is as follows:

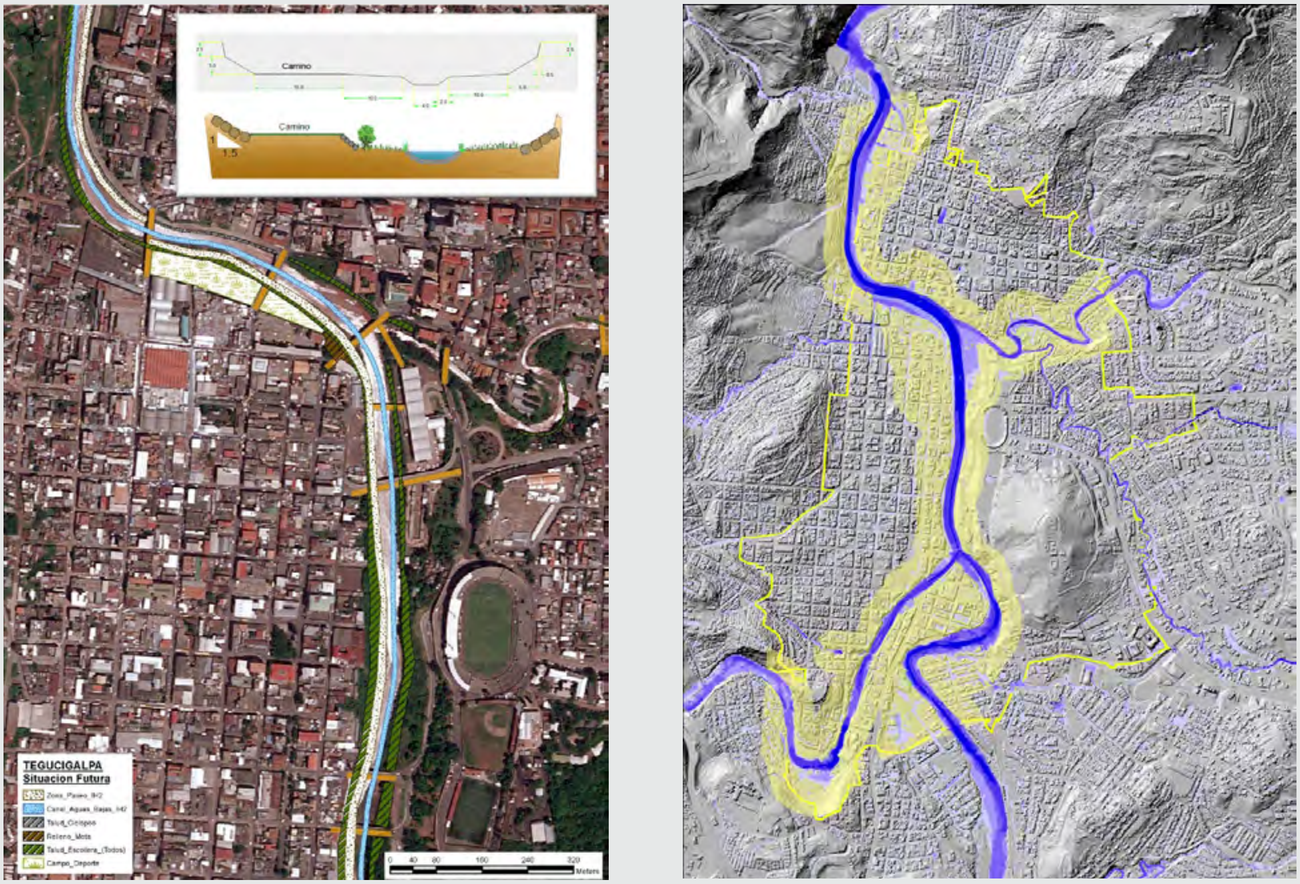


Table 43 | Left) Outline of the standard plan and section proposed for the channel of the Choluteca river. Right) Influence area of the works (yellow shade), with an indication of the peak depths for T=50 years in the intervention scenario 2050.

INVESTMENTS	CAPEX	OPERATING COST	DURATION	LIFE SPAN
DESCRIPTION	(MUSD)	(MUSD /year)	(Years)	(Years)
FLOOD CONTROL (HYDRAULIC WORK)	12.05	0.12	3	100
URBAN CONDITIONING (BASIC)	5.67	0.06	3	50
SECURITY, CLEANING AND PROMOTION	0.10	0.10		
TOTAL	17.82	0.28	3	

Table 20 | Appraisal of the investments related to works.

BENEFITS		
DAMAGE REPAIR SAVINGS	2.69	MUSD/year
REDUCED DAMAGE FROM TRAFFIC INTERRUPTION	0.18	MUSD/year
REDUCED DAMAGE TO MARKETS	0.0722	MUSD/year
TOTAL ANNUAL BENEFITS	3.12	MUSD/year
SOCIAL BENEFIT ON INVESTMENT RATIO	15%	MUSD/year

Table 21 | Benefits in the different aspects.

The following table summarizes the benefits obtained for the following aspects considered:

DISCOUNT RATE	12%
TOTAL DISCOUNTED INVESTMENTS (INV)	17.8 MUSD
TOTAL DISCOUNTED BENEFITS (BEN)	22.5 MUSD
NPV	4.7 MUSD
IRR	15.62%
RETURN ON INVESTMENT (BEN/INV)	1.26
BREAK-EVEN PERIOD	15 years

Table 22 | Profitability thresholds.

By combining the above cost and benefit values, and applying a 12% discount rate, as recommended by IDB in assessing investments, profitability thresholds are obtained (NPV, IRR, return on investment and break-even period). The profitability thresholds obtained are as follows:

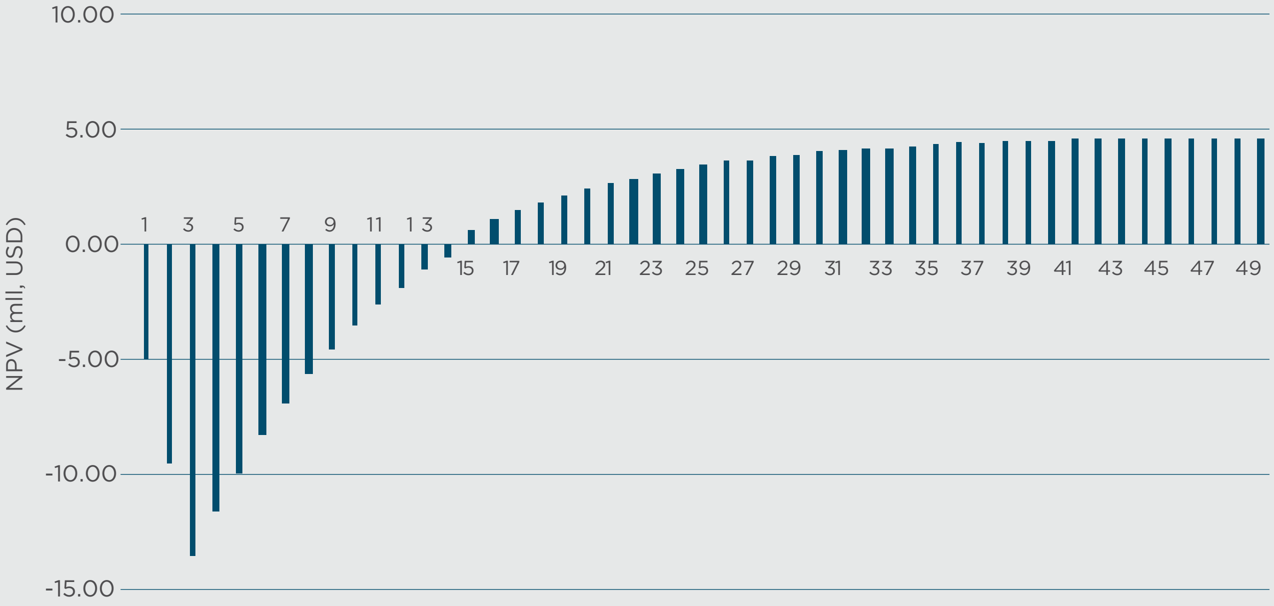


Figure 44 | Evolution of the net present value of the investment from the works kick off.

The flood control works in Choluteca river at the point where it runs across the center of Tegucigalpa account for a net benefit of 4.7 MUSD, an internal rate of return of 15.6%, which exceeds the one stipulated by IDB, and a ROI of 1.26; the time necessary for the benefits to exceed accumulated costs is 15 years. The figure below portrays the accumulated cash flows and clearly shows the break-even point.

Selecting a social discount rate

Most multilateral financial organizations, including IDB, as well as agencies from different developing countries, recommend using social discount rates ranging between 8 and 15% when conducting an economic assessment of projects; in the case of IDB, the rate adopted is 12%, based on an estimation of the capital opportunity cost.

These figures can be valid for projects on an intra-generational scale, with results in the short and medium term, but are usually unfit for risk reduction projects. The problem of the sharp decline of the compound-interest discount rate is particularly evident in this type of projects because they usually include large infrastructures whose life span and expected effects exceed one century. Therefore, some countries, especially in the developed world, have adopted discount rates between 1 and 4% for projects with a long life span, including those related to climate change and water (for a thorough analysis of current practices see Asian Development Bank, 2013). In addition, a large group of experts in environmental economics have recommended the use of a time-decreasing discount rate for projects affecting multiple generations, as already done in some countries like the United Kingdom and France (Arrow et al. 2013).

Based on the experience gained with the ESCI, it seems advisable to adopt either a reduced discount rate (below 4%, as a guiding percentage), or a time-decreasing discount rate (e.g., a hyperbolic-type discount rate) in risk reduction projects with multi-dimensional and long-term effects. Otherwise, any benefit not yielded during the first decade after the works are finished will barely reflect in the efficiency indicators.

Incorporation of human damage and equity factors

In disasters related to natural events, human damage may be as significant as economic damage, especially in places with high poverty rates, where the value of the material assets at risk tends to be low. Quantifying this type of damage in monetary terms is controversial and poses a moral dilemma, but ignoring them at the time of discriminating between different alternatives is not appropriate either.

There are several methodological procedures to solve this issue, and all of them are valid at first glance, provided that they are clearly presented as a hypothesis of work:

1. Monetary evaluation of the value of human life. Fatalities and injured people may be translated into money following, at least, two reasoning lines: 1) as a loss of potential economic productivity associated with early death (the human capital method), and 2) as a value allocated by insurance companies to human life or damage. This way, they are directly incorporated into the cash flows of the CBA.

2. Quantifying human damage through a non-monetary measure, such as disability-adjusted life years (DALY), and conducting a cost-effectiveness analysis of the different alternatives based on this parameter, as a complement of the strictly monetary cost-benefit analysis. Thus, the CBA would have two separate components that do not integrate into one single aggregate magnitude.

3. Not to directly quantify human damage, but introduce a weighing factor for economic damage (especially damage to buildings) that considers the value lost in relation to the purchasing power of the people impacted. For example, a loss of USD 1,000 in a household whose average income is USD 2,000/year may be equivalent to a loss 10 times greater in a household with high purchasing power, and the CBA could reflect this reality. While this procedure does not actually assess human damage, it does introduce an equity factor in the effect of the measures, which partially corrects the invisibility of the most disadvantaged classes in a conventional quantification of material damage. On the other hand, the weighed damage figures no longer reflect the actual replacement value of the assets (it is more of an equivalent damage, adjusted by purchasing power parity).

Uncertainty associated with a sequence of extreme events

The most important benefit of a set of risk reduction measures is usually the damage avoided by the proposed actions, which will be distributed over time according to a random – a priori unknown – series of extreme events that will take place once the works are completed (or during their execution). The fact that the sequence of catastrophic events is unpredictable greatly affects the results of the analysis due to the social discount rate, which attaches more significance to the events that are close in time. Therefore, a measure to neutralize a 50-year flood will be highly profitable from the CBA perspective if such event occurs right after the works have been completed, and worthless if it takes several decades to occur. Using mean annualized damage values does not solve the problem: the profitability indicators that result from considering annual average losses (or pure risk premium) are not good estimators of the average profitability obtained through probabilistic methods.

As a conclusion, a rigorous CBA of a risk reduction measure program should attempt to characterize the density function of each alternative, consistently considering all the uncertainties involved and, especially, the sequence of events that will be mitigated. When dealing with probability functions instead of single profitability values, the comparison to pick the most favorable one is not straightforward; a valid criterion that can be adopted in this probabilistic framework is to use the conditional value at risk as a profitability parameter (Garcia et al., 2016).

Joint evolution of damage and socio-economic scenarios

The CBA techniques require a long-term assessment of both the relevant hazard, including the effect of climate change, and the vulnerability factors. Usually, the uncertainties associated with both risk components are considered independently, and development scenarios for climate variables are defined independently from socio-economic evolution scenarios. However, a more exhaustive analysis (see section 5.2) points at the existence of two feedback loops that relate risk factors over time:

1. The damage caused by extreme events generates responses in the physical and socioeconomic media which alter the vulnerability factors and, therefore, the subsequent risk/damage conditions.

2. The damage derived from extreme events generates responses that alter the physical medium, which in turn alters the physical pathways of the hazard and, therefore, the hazard factors that determine risks.

These pathways of co-evolution of the hazard and vulnerability over time are very difficult to model and introduce another source of uncertainty in future damage forecasts, which is transferred to the cash flows that support the CBA. A particularly complex example of these pathways (which is also relevant for purposes of quantifying damage) is the pace and way of re-population of the areas that have been devastated by a natural disaster, in the absence of significant risk reduction measures.

Faced with the challenge of the feedback existing between the socio-urban system and risk generation, it is possible to act in two antagonistic ways:

1. Double technological efforts and propose CBA models that dynamically operate on the results of the urbanism-risk joint evolution models (probabilistic, if possible). This approach is under investigation and is starting to yield interesting results, although it is data-intensive and complex to apply.

2. Recognize the limitations of the technocratic paradigm and put it in the background – at least for these purposes –, and address the problem as what it ultimately is: a debate on the nature of a historical process, in this case from the specific perspective of the evolution of cities under risk conditions.

7.3 Semi-quantitative methods for selecting alternatives

As an alternative to the already-described CBA techniques, which are essentially based on reducing the problem to a single economic dimension, there is a set of methods that try to preserve the multi-dimensional essence of the decision-making process until the last minute. The multi-criteria analysis techniques (MAT) usually start by conceptualizing a problem according to the following elements:

1. A set of alternatives Ai, from which the most suitable one is sought to be selected.
2. A set of selection criteria Ci, each with a ranking scale of its own. The scales can be either quantitative or qualitative.
3. An evaluation of each alternative in relation to each criterion, which results in an assessment matrix.
4. Some Wi weights associated with such criteria, which express the relative importance of each criterion in the final decision-making. Their sum must be the unit.

If we focus the discussion on the application of the MATs to risk reduction measures, the first two previous points (alternatives and selection criteria) are usually fixed by the people in charge of the analysis or of coordinating it, while the assessment of alternatives and the weights must, a priori, be participatory, as intermediate results of the decision-making.

There follows a description of the main steps in the execution of a multi-criteria analysis and how they relate to each other to meet the ultimate objective of selecting the most suitable alternative.

1. Definition of alternatives

Although this subject has been dealt with in previous sections, it is important to emphasize that to define alternatives from a MATs perspective it is necessary to determine and differentiate their characteristics in relation to the criteria upon which the selection will be based (see following heading). Therefore, there should be coherence and consistency in terms of the information supplied in all the subjects that are of interest. This may require gathering data on the alternatives that were not included in their initial characterization or completing the available studies to cover aspects that had not been analyzed.

2. Definition of selection criteria.

Two related problems need to be addressed: selecting criteria and defining the units of measurement of those criteria. As for the first problem, in risk assessments some of the following criteria are usually identified as the most relevant:

Functionality criteria:

- Efficiency in reducing economic risks.
- Efficiency in reducing human risks.
- Climate change vulnerability of the design.
- Time required for implementation.
- Implementation (building) risks.
- Technological risks and probability of failure during the operation phase.
- Life span.
- Possibility of alternative uses.
Economic criteria:
- Return on investment.
- Investment break-even period.

- Re-distributional effect of the investment.

Other criteria:

- Environmental impact.
- Social assessment and perception.
- Impact on the urban environment and degree of integration into planning.
- Synergies with other ongoing measures.

The selected criteria must be coupled with qualitative or quantitative rating scales that must ultimately be comparable to each other. This is equivalent to the problem of converting indices into risk levels, as shown in section 5.3. Since in this case usually the starting point is not information in the form of indices for all the selected criteria, and considering that some of the criteria may not be quantifiable, it is common practice in this context to define a single qualitative scale for all the criteria (e.g., from 1 to 5, as in section 5.3, or from 1 to 10). Finally, it is worth noting that when introducing a large number of criteria in the decision-making, the information required to evaluate them increases proportionally.

3. Assessment of alternatives and weights.

This is the key activity in the decision-making process, which supports multiple variations depending on the number and profile of the players involved. In the first place, it is necessary to guarantee that the team of participants has a consistent and sufficient understanding of the starting information, upon which they will base their judgments. This basic condition is not automatically met in many cases, especially when open participatory processes involving several social players are organized. In addition, an attempt should be made to form an assessment group with a roughly even participation of all sectors of the relevant activity (for process with general public participation), and all the areas of expertise related to the problem (for processes involving an expert panel). In the assessment of alternatives, it is important to avoid biases derived from the existence of majorities of a given profile of social or expert players. There is a large variety of techniques to obtain the assessments, even if only in terms of their format:

- Personal surveys.
- Telephone surveys.
- On-line or paper questionnaires.
- Face-to-face meetings where questionnaires are completed or other techniques are used.

Notwithstanding the mode of participation, the techniques to get the assessments may be simple (one-way) or have a certain degree of feedback – for instance, in two rounds, with the first one aiming at getting a first judgment and the second one to get it validated in light of other evaluations. These procedures are more complex and lead to the so-called Delphi methods (Linstone and Turoff 1975), which may include debates and other interaction instruments.

Usually, the assessment of different alternatives is done in a sequential and independent way, according to the criteria selected and the allocation of relative weights to such criteria. As regards weights, consensus is usually sought among the participants in order to fix some values – which in case of controversy tend to be similar – to strike a balance between the different dimensions of a problem. As for the criteria-based assessments, it is also advisable to reach a consensus, but it tends to be more difficult and to take more time. Therefore, usually all the opinions – associated with individuals or groups – are gathered, and a statistical analysis of the results is conducted.

Some MAT applications introduce the relative weights of the decision-making criteria as technically imposed factors, leaving the assessment of alternatives in relation to those criteria as the only free parameters. This leads to noticeable biases in the results and diminishes the participants' capacity to contribute their vision of reality with its associated hierarchy of values – which cannot be predefined.

4. Analysis of results and presentation of the selected alternative.

Following the previous tasks, the weights and average ratings of each factor may be combined to arrive at a final rating of each alternative in a single and limited scale, so that the option with the highest rating is the one that, in theory, better meets the requirements sought. It is important to analyze and assess the results obtained running some tests to avoid inconsistencies or undesired effects:

- Sensitivity of the optimum result to the relative weights assigned to the criteria. It is advisable to apply a simple sensitivity analysis using other families of acceptable weights to establish if the solution obtained is not too sensitive to them and, therefore, unstable.
- Polarization of positions. If the results of the criteria-based assessment have been obtained averaging the inputs of different players, a given conclusion (e.g., that the environmental impact of an alternative is medium) may not reflect a dominant opinion (nobody believes that said impact is medium), but be the result of combining two large opposing groups (a group that considers the impact to be very high and the other to be very low) that neutralize each other when calculating the mean. In this case, a consensus must be reached before moving forward. In general, whenever the standard deviation of positions in relation to an aspect of some alternative is high, the result must be revised and a debate should be reopened if necessary.

The ESCI studies combine cost-benefit and multi-criteria analysis techniques to identify the most suitable alternative. In general, the CBA is the most technical tool and, as such, is usually included in the base studies as a natural extension of the quantitative risk results. However, it is not easy to incorporate public engagement elements in the CBA, although it does enable the inclusion of survey results or field data to improve the estimation of the monetary value of certain assets. An advantage of the MATs vis-a-vis the CBA is that they can be naturally integrated in the public engagement processes and social outreach workshops. By homogenizing and combining scales for rating alternatives against different criteria, as done by the MATs, it is possible to build an apparently solid bridge between technical results and the colloquial language used by any type of person (e.g., the X initiative would be very favorable or hardly favorable to solve the flood issue in neighborhood Y). However, under this apparent confluence of technical and public engagement elements there is the problem of the representativeness and comparability of opinions that stem from very different sources with highly uneven levels of knowledge.

The CBA techniques require a long-term assessment of both the relevant hazard, including the effect of climate change, and the vulnerability factors.

Conclusions —

Urban conglomerates in Latin America and the Caribbean, with their wide range of climates, landscapes and socioeconomic conditions, show an increasing trend towards experiencing natural disasters. Every year, floods and hurricanes produce uncountable damage in the region, widening social gaps and ultimately limiting or hindering the countries' economic and social development. This problem has become even more critical with climate change.

This document has attempted to provide a systematic description of a methodological procedure to carry out studies on the hydroclimatic risks that affect cities, with a special emphasis on climate change and what climate change stands for from a risk reduction perspective. The proposed techniques and tools have been used in studies conducted in many cities that are part of the network of Emerging and Sustainable Cities (ESC, 2011-2018). ESC is an innovative initiative undertaken by the Inter-American Development Bank to strengthen the adaptation capacity and governance of some of the most dynamic cities in LAC, which sought to address development-related problems before their scale renders them uncontrollable.

Through boxes exemplifying the application of the presented work methods, this document navigates this diverse region of the world, covering from Andean cities that are served by disappearing glaciers, to areas built on ancient mangroves which are exposed to hurricanes, and settlements on riverbanks that are structured by large rivers that may change their course anytime and recover the space that once belonged to them. After setting out on a journey across such different places and territories, the traveler is left with mixed impressions and feelings at the time of writing out their travel log. On the one hand, there are the great opportunities that this subcontinent has to overcome the challenge posed by the intermediate income levels that have characterized it over the past decades. These opportunities mainly lie in a proper administration of natural resources, including disaster management, and in the channeling of the human capital supported by a relatively young, diverse and increasingly educated population. However, it should also be admitted that, taken as a whole, the reality of this region can be overwhelming due to the variety and abundance of physical and ideological ecosystems it hosts, to the point that any attempt to classify or rearrange this reality, or to propose models or general recipes applicable to all the visited places, would seem overly ambitious. This dichotomy has been reflected in the proposed methodology by combining two approaches that are usually presented separately, but which are starting to share an increasingly common space of debate: the technical and the humanistic approaches, with the latter being understood as everything that the positive science may contribute.

The combination of the technical approach with that of the positive science does not entail an indiscriminate mix of concepts and should not lead to confusion. In fact, risk studies should harness the rigorousness contributed by science when it comes to explaining physical processes, from climate and its alterations, to the failure mechanism of a dam, or the propagation of water in an urban area. Technical experts may – and should – contribute their knowledge when conducting risk studies to diagnose the scale, trend, and form of materialization of natural phenomena, and they are also the ones responsible for defining the characteristics of the fittest infrastructure to reduce them, if required. However, the technical approach shows clear shortcomings when it comes to understanding the mechanisms and historical processes that are generating risks, which in turn provide the key to designing the programs of measures aimed at reducing them. There are also limitations to the capacity to perform essential tasks which exceed the realm of engineering: changes in the regulatory framework, reforms of the institutional map, or the review of the type of messages that public administrations send to society, with a view to reducing risks.

More avenues are opening up for a closer relationship between disciplines and approaches to improve risk studies and intervention proposals. Green infrastructures, or ecosystem-based solutions, are progressively gaining ground and have forced traditional engineers to leave their comfort zone and engage in dialogue with biologists, ecologists, landscape designers, and architects. Sociologists and economists are progressing towards the identification of the patterns that rule people's decision-making (on economic or other matters), which are imbued with considerable irrationality, and are also finding possible ways to promote coherence in citizens' behavior through timely activities and messages. Nowadays, thanks to the information and communication technologies, real-time messages can be delivered to target groups that are dynamically defined based on their location, place of residence, age, type of household, and other criteria. The full potential of new technologies has not yet been applied to risk reduction, and significant progress is likely to be seen in this regard in the upcoming decades, covering both early warning systems and applications to facilitate post-disaster evacuation and assistance operations.

To meet the demands of modern societies in a changing environment, technical experts educated under the deterministic paradigm of risk management will need to learn increasingly complex statistical techniques in order to mainstream uncertainty into their calculations, without trading off the quantification of phenomena. Therefore, another recurrent issue in this document is the randomness of natural phenomena and how to make up for the incomplete knowledge of some of the factors that determine risks and condition the effectiveness of the measures taken to reduce them. Ultimately, even with the adoption of probabilistic approaches, there will always be an irreducible degree of uncertainty in data and numerical models, and thus the validity of results will be tied to the assumptions made for the modeling exercise.

An implicit conclusion derived from what has been presented in this document is that the causes, as well as the possible solutions, to urban risks are nearly always found outside of the affected places, and often outside of the cities themselves. It is therefore necessary to adopt a systems approach, instead of intending to solve the problems by directly working on the exposed areas.

In the LAC region, as in other places, damage from natural disasters and poverty tend to go hand in hand. Poverty and risk reduction are closely tied and it is also practical to think of risk reduction as a sectorial tool aimed at preventing economic hardship from being worsened by other calamities. Poverty places people in a disadvantaged position to fight natural catastrophes. In addition, it is important to inquire into the decision making-processes and scope of action of the population. Decisions like settling in an unstable slope or a riverbank are critical from an urban risk perspective and respond to a rationality that is circumscribed to a context which is necessary to explore.

Natural phenomena have shaped the mentality of the different civilizations over time, along with their systems of government, religions and customs; cataclysms and slow-onset hydro-geological processes have dictated the rise and doom of great empires. Nowadays, for the first time in the history of mankind, increasingly globalized, technified and largely urban societies are facing the challenge of accelerated climate change worldwide, with partly unpredictable consequences. We hope this document proves useful in highlighting the urgency of the situation and provides national and municipal governments, and other institutions and stakeholders, with a set of basic criteria and guidelines to play their part in this new era and progress towards more sustainable and resilient cities and communities.

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Acronyms —

ARP	At-Risk Population
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BV	Building Value
CI	Critical Infrastructure
DSV	Dwellings Stock Value
DTM	Digital Terrain Model
EAL	Expected Annual Loss
ENSO	El Niño Southern Oscillation
ESC	Emerging and Sustainable Cities
ESCI	Emerging and Sustainable Cities Initiative
EV	Equipment Value
FEF	Flow Exposure Factor
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gasses
GIS	Geographic Information System
GPM	Global Precipitation Measurement
HURDAT	HURricane DATabase
IBTrACS	International Best Track Archive for Climate Stewardship
IDB	Inter-American Development Bank
IDF	Intensity-Duration-Frequency
IFSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change

IRR	Internal Rate of Return
LAC	Latin America and the Caribbean
LIDAR	Laser Imaging Detection and Ranging
LV	Land Value
MUSD	Millions of United States Dollars
NEX-GDDP	Earth Exchange Global Daily Downscaled Projections
NOAA	National Oceanic and Atmospheric Administration
NUV	Net Updated Value
OECD	Organisation for Economic Co-operation and Development
PML	Probable Maximum Loss
RCM	Regional Climate Model
RCMs	Risk Construction Mechanisms
RCP	Representative Concentration Pathway
REV	Real Estate Value
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
SST	Sea Surface Temperature
SV	Systems value
TRMM	Tropical Rainfall Measuring Mission
UNDP	United Nations Development Programme
UNICEF	United Nations International Children’s Emergency Fund
VARC	Value at Risk in a Collapse (flooding o windstorm)
VRSFW	Value at Risk for Slow Flooding or Wind Without Collapse
WHO	World Health Organization
WTO	World Trade Organization

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