Public Investment Profile for Disaster Risk Reduction: a Macro-Economic Study

Environment, Rural
Development and Risk
Management Division

Inter-American Development Bank

TECHNICAL NOTE Nº

IDB-TN-1889

March 2020

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Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library
Public investment profile for disaster risk reduction: a macro-economic study / Inter-American Development Bank.
p. cm. — (IDB Technical Note ; 1889)
Includes bibliographic references.
1. Disaster relief-Economic aspects-Latin America. 2. Emergency management-Economic aspects-Latin America. 3. Natural disasters-Risk assessment-Latin America. 4. Climate change mitigation-Economic aspects-Latin America. 5. Public investments-Latin America. I. Inter-American Development Bank. Environment, Rural Development and Risk Management Division. II. Title. III. Series.
IDB-TN-1889

JEL Codes: Q54,
Keywords: Climate Change, Natural Disasters Management, Global Warming.

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The development and publication of this document was possible through the Regional Technical Cooperation RG-T2434, financed by the Multidonor Disaster Prevention Trust Fund

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1 INTRODUCTION

The technical instrument *Investment Profile for Disaster Risk Reduction (DRR Investment Profile)* is the product of the study "*Development of a Public Investment Profile for Disaster Risk Reduction: A Macro-Economic Study*" carried out by the Inter-American Development Bank (IADB) through the Technical Cooperation RG-T2434 from 2014 to 2018. The study's objective was to develop a technical instrument to carry out comparative analyses on the economic benefits of different investment measures in Disaster Risk Reduction (DRR), assessing the benefits from public investments that mitigate the economic and social impacts of disasters sustainably. This instrument supports decision-makers in the allocation of public budget to different strategies in disaster risk mitigation, risk retention and transfer (by considering different financial instruments) both at national and local levels.

This document presents a conceptual model to optimize financing for DRR - amongst four possible options - over different time periods: a) investment in risk mitigation measures, b) design of a reserve fund to cope with the immediate needs for emergency attention and restoration of basic services, c) engage on a contingent credit financial instrument to cover certain loss layers, and/or d) purchase insurance to transfer risk to a third party. Each possible option comes with an estimation of costs and benefits to choose the most efficient option (i.e. the one that yields the highest ratio between benefits and costs, subject to a budgetary constraint or not).

This document is organized as follows: Chapter 2 provides information on the development of the model based on a literature review. Chapter 3 proposes a conceptual model and, Chapter 4 presents the methodological framework to incorporate risk mitigation measures in this conceptual model. Finally, Chapter 5 addresses a methodology to obtain the loss exceedance curves (LEC) that evaluate the efficiency of mitigation measures. The model seeks to reflect changes in the LEC through variations in specific parameters.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The number of disasters[1] that have occurred globally has been increasing over the last decades and are reflected in larger economic losses. The World Bank (WB) has estimated accumulated losses of around US$4,000 Billion (US$4,000,000,000,000) during the last 30 years, of which only 9% have occurred in developing countries. However, 48% of the fatalities and affected people (i.e. injured, displaced) during the same period occurred in developing countries (WB, 2014).

When measured in absolute losses, the largest disasters usually occur in developed countries due to the high amount and cost of the exposed assets. Nevertheless, when compared with the Gross Domestic Product (GDP), the overall impact of disasters in these countries is not as significant as in developing countries, since the share of losses that have occurred is lower. For instance, the impact of Hurricane Katrina in 2005 in the economy of the United States of America (USA) accounted for 1.1% of its GDP. The Kobe earthquake in Japan in 1995, equaled to 3.2% of the GDP of Japan, whereas the impact of disasters in less developed countries is higher. In 1988, hurricane Gilbert reduced the GDP of Saint Lucia by 365% (Cummins and Mahul, 2008).

The cost of the financing instruments to cope with disasters are higher in developing countries than in developed ones. For example, the USA's disaster assistance policy is financed with fiscal resources (and debt). However, the overall impact of these events in the country's total budget is low due to the capacity to reallocate budget in emergency situations (Moss, 2010).

To help address this, various multilateral organizations, and affected country governments, have developed initiatives to promote disaster risk management financial strategies, using typically two approaches. The first consists in stimulating the development of local insurance markets, bringing them closer to the main productive sectors of each economy and to the population in general. The second is to promote disaster financial instruments operated by governments, especially those related to critical assets (e.g. public infrastructure for

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[1] The United Nations Office for Disaster Risk Reduction defines "disaster" as a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts (https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf).

transportation, energy, education, health and lifelines, among others) to reduce negative impacts caused by catastrophic events.

While these efforts have seen significant achievements and milestones in disaster risk financial management in some regions (e.g. Caribbean Catastrophe Risk Insurance Facility - CCRIF), the management of disaster risk still requires improvements in areas exposed to hazards. Evidence suggests that governments spend more on responding to emergencies than on *ex-ante* investments on disaster prevention, regardless of their level of economic development. This is possibly related to short-sightedness of taxpayers, or voter preferences in favor of immediate spending after an event (WB, 2010). The large amount of media information at the time of occurrence of a disaster could also be a factor of influence, compared to the information available on the benefits of investing in long-term disaster prevention programs (Moss, 2010).

Traditional economic theories based on Arrow and Lind (1970)[2] suggest that government investment decisions should be risk neutral because both returns and investment costs are distributed between all economic agents so that the tendency of the risk premium is zero for all users. However, the many complexities and particularities of each country or region, magnified by their corresponding economic development levels, led to conceptualizing the government as risk-averse rather than as risk-neutral. This latter attitude would promote an active public risk management, which at the same time, generates value to society.

For example, Ghesquiere and Mahul (2007) and Mechler (2014) argue that the relevance of disaster risk management in developing countries, is strongly correlated with the losses that individuals face in the event of a disaster and the limited government capacity to obtain the necessary liquidity to cope with the associated costs after its occurrence. This is why governments should adopt *ex-ante* disaster risk management practices.

The economic literature on this subject is still under development, and it is currently even exploring the effects of behavioral patterns that do not adhere to traditional economic rationale. However, it is safe to assume that countries, consciously or unconsciously, have adopted a role of effective and efficient disaster risk managers.

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[2] Based on Arrow-Lind's (1970) public investment theorem, governments should apply a risk neutral policy in the evaluation of public investment when evaluating public projects based on expected net benefits.

For this reason, it is relevant to ask the following questions: how should disaster risk be managed? What strategies and tools are available for governments in doing so? What instruments should be included in a robust disaster risk management strategy? How should the efficiency of these instruments be assessed? Is it better to assess each strategy or instrument individually or jointly? If there is a metric to distinguish between strategies, how can the *best* strategy be identified? What should the scope and meaning of the *best* strategy be, according to a given metric?

This methodology offers answers to all these questions, based on the most recent conceptual and practical models that have been published to date. The literature review on the financial management of disaster risk is grouped into five major topic areas[3]:

1. Loss assessment, focusing on estimating losses caused by disasters and their consequences in the economy.
2. *Ex-ante* risk mitigation and its economic benefits, by analyzing decisions to invest in risk mitigation measures based on costs and benefits.
3. Risk retention and transfer, to understand financial capacities to retain risk within a government.
4. Review of different experiences on the use of risk transfer financing instruments, and,
5. Review of available methodologies for evaluating optimal strategies comprised by disaster risk mitigation, retention and transfer actions, that seek to achieve efficient *ex-ante* management of catastrophic losses.

2.2 DIRECT AND INDIRECT LOSS ASSESSMENT

The sustained increase in the number, intensity and severity of disasters that have occurred in the past decades, have driven several international and multilateral cooperation organizations to increase the understanding of the estimation of disaster losses, and to assess potential financial needs of affected countries.

In the late 1980s, the European Commission conducted several studies on this subject. In the 1990s, the World Bank (WB), the Inter-American Development Bank (IADB) and the

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[3] The textbooks by Kwon and Skipper (2007), Harrington and Niehaus (2004) and Vaughan and Vaughan (2001), among others. classify the instruments to manage disaster risk as of: mitigation, retention and transfer.

Asian Development Bank (ADB) assessed the economic impacts of disasters focusing particularly on the need to disaggregate losses at national, regional and local levels.

From the 1990s onwards, some methodologies were standardized to estimate *ex-post* disaster-caused losses. The United Nations Economic Commission for Latin America and the Caribbean (ECLAC) developed a methodology for estimating damages and losses due to disasters (ECLAC, 2003; Moore, et al., 2014) dividing the estimation into two large categories: 1) direct losses and, 2) indirect losses. This methodology laid the foundations for several analyses to estimate losses after the occurrence of an event.

The mid-1990s also saw an emergence of private companies[4] specializing in estimating *ex-ante* losses through prospective and probabilistic approaches that allowed to estimate the demand for insurance and reinsurance portfolios. Over the decades, this *high-resolution* approach (from the perspective of the detailed representation of the exposure), has been implemented not only in the insurance and reinsurance sector, but also in public institutions, mainly in developing countries.

Based on the literature review, disaster losses can be described using the following expressions:

$$L = f(Direct\ losses, Indirect\ losses) \tag{2-1}$$

$$L = f(h, e, v) \tag{2-2}$$

Expression (2-1) summarizes ECLAC's methodology as it estimates the overall Loss (*L*), as a function of the direct and indirect losses, whereas expression (2-2) estimates the probable Losses (*L*) as a function of: the natural hazard (*h*), the characteristics of the exposure (*e*) and its associated vulnerability (*v*). Disaster losses can be estimated using two approaches, one being the estimation of losses through *ex-post* evaluations, whereas the second carries out *ex-ante* estimations based on structural information of the individual or grouped assets. Expression (2-2) conceptually represents the basis for a probabilistic risk assessment.

The generic form proposed to assign a metric to disaster risk has to do with the variation of losses (*R)*. In the literature of financial management of disaster risk, *R* has been the main component of analysis.

$$R = Variation(L) \tag{2-3}$$

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[4] AIR Worldwide, ERN, EQCAT and RMS are the main companies.

According to the literature on loss estimations with *ex-post* approaches, Cavallo et al. (2010) carried out a comparative analysis between different countries and disasters to estimate the variations in the GDP after the occurrence of a catastrophic event. Authors classified disasters into two types: those with "extremely" large and low values of L. The rationale is that as per economic growth theory, it is implied that an abrupt change in the capital stock caused by its destruction is reflected in a decrease of the GDP growth. The authors have found that this theory can only be verified with events that cause “extremely” large losses.

Barro (2006; 2009) concluded that disasters of extreme severity and low frequency (a particular set of L) have a larger impact on economic wellbeing than those caused by economic and financial fluctuations. Cavallo et al. (2010) defined a form for expression (2-1), especially for the first part of the functional relationship (direct losses). These direct losses can be described as:

$$DIS_{it} = \propto + \beta X_{it} + \varepsilon_{it} \tag{2-4}$$

where DIS_{it} is the extent of direct damages caused by a disaster in the i^{th} country during time t; X_{it} is a vector of variables that measure the damage intensity, $\propto$ is the intercept and ε_{it} are the errors. In general, the literature review found that studies used econometric approaches that have adopted the form of expression (2-4). Kahn (2005) performed a specific case analysis on (2-4), and concluded that disasters are less frequent and mortality rates are lower in developed countries when compared with developing countries. Kellenber and Moborak (2008) established a non-linear relationship for (2-4) through an analysis between economic development and vulnerability. They found that the less developed a country is, the higher the risk such as in marginalized human settlements in hazard prone areas. Sutter (2005) confirmed the findings by Kellenber and Moborak (2008) after a study in the USA.

Other researchers have carried out similar analyses by including institutional factors (Kahn, 2005; Skidmore and Toya, 2007; Raschky, 2008; Strongber, 2007). It is worth noting that Besley and Burgess (2002), Eisensee and Stronberg (2007), Healey and Malhotra (2009) and Plumper and Neumayer (2009) performed similar analyses, including variables that describe the relevant economic policy that consider the risk within the affected economy by a disaster.

Indirect losses in expression (2-1), according to Cavallo et al. (2010), can be summarized in the following expression:

$$Y_{it} = \propto + \beta X_{it} + \gamma DIS_{it} + \varepsilon_{it} \tag{2-5}$$

where Y_{it} represents the impact variable, for example the GDP in the i^{th} country for time t; X_{it} is the vector of control variables that potentially affect Y_{it}, whereas DIS_{it} measures the intensity of the catastrophic event and ε_{it} are the errors. Any other variables that have an impact on the economy, can also be added to expression (2-5).

Using the approach of expression (2-5), Roddatz (2007) analysed the effects of dynamic shocks in the GDP of developing countries in the short term. While Noy (2009), studied the adverse effects of a similar analysis on expression (2-5). Noy (2009) used indicators for developed countries such as high education rates and income levels as well as open market indicators, among others, which also led to conclude that developed countries are less affected by disasters than least developed ones.

Hochrainer (2009) and Loayza (2009) analyzed, through self-regressive vectors and generalized moment methods, respectively, the impact of disasters on GDP for a certain timeframe. A relevant occasional finding is the positive change in GDP growth after a disaster. This is an interesting subject since it contradicts the classical economic theory that had already been documented by Albala-Bertrand (1993) and Skidmore and Toya (2002).

The analyses on equation (2-5) have also acquired a sub-regional approach, such as in Strobl (2008), who performed an analysis for some counties in the USA. Other studies, such as those by Rodriguez-Oreggia et al. (2009) and Mechler (2009), have incorporated additional variables such as poverty measurements and level of human development.

It should be noted the literature reviewed concords and establishes that for expressions (2-4) and (2-5), there is a negative impact between the variables that describe the disaster and the variables that describe the economy or its growth. In other words, in the literature, model analyzes describe the relationship between short-term disaster losses and a long term (negative) economic growth.

Regarding expression (2-2), the most innovative analysis is the one conducted by Clark et al. (2002) that reviewed the history and development of the catastrophe risk (CAT-Risk) modeling industry. As indicated before, this type of analysis uses a modular approach (Grossi and Kunreuther, (2005) to estimate, h, e and v through specific methodologies that describe the behavior and geographical extent of the intensities of the natural hazards, the characteristics of the exposed assets and their vulnerability. Through scientific knowledge of natural hazards and civil and structural engineering techniques, it is possible to obtain probability curves that provide relationships between damages and losses and the hazard intensities (Pflug and Roemisch, 2007).

The probabilistic approach, with a functional form as the one shown in equation (2-2), emerged in the 90's to provide estimates of potential losses to insurers and reinsurers. It was not until the mid-decade of the period from 2000 to 2010 that it was used to study the economic effects of disasters in developing countries. In 2005, the CCRIF - the first multi-country catastrophe risk insurance pool for the Caribbean Islands used the approach. A year later, the Mexican Government made a similar analysis to understand the financial needs on public funding for earthquake risk (FONDEN, 2012).

Over time, several efforts have been made to standardize the approach for estimating *L*. In fact, the World Bank (WB), United Nations Office for Disaster Risk Reduction (UNDRR), United Nations Development Program (UNDP) and Inter-American Development Bank (IDB), promoted the development of CAPRA (Comprehensive Approach to Probabilistic Risk Assessment) between 2008 and 2010 (see www.ecapra.org). CAPRA is an open-source platform and it uses the approach applied by the main risk modelling companies used by insurers and reinsurers. This platform differentiates itself in that it uses portfolios of assets that characterize developing countries from the perspective of Governments and other users.

Risk assessments obtained with this modeling approach have higher precision and resolution. They incorporate geo-reference and structural description of the exposed assets and use the most recent models that describe natural hazards. There are examples of the use of this approach for catastrophe risk assessment, at different scales in Kenya, Ethiopia, Turkey, India, Romania, Mongolia, the Caribbean Islands, the Pacific States, and some African Union countries, among others (WB, 2014).

When *L* is quantified, it can be studied with probabilistic models. It is possible to simulate, and thus analyze, the behavior of extreme values with a high degree of detail, so it is possible to describe *R* (see equation 2-3).

As a conclusion of this theoretical summary, it is possible to describe *L* through plots with occurrence probabilities and/or exceedance rates, which are valuable and mandatory inputs when defining proactive disaster risk management strategies. The following sections summarize the findings that address the issue of influencing potential losses by knowing their probability distribution (empirical or analytical).

2.3 MITIGATION MEASURES AND THEIR BENEFITS

Risk mitigation is widely studied either within a comprehensive disaster risk management strategy as well as independently as a measure of infrastructure investment to reduce future losses.

Shyam (2013) found that the most used method in the risk mitigation literature is the Benefit-Cost Analysis (BCA), either measured in absolute terms or as a ratio (i.e. Benefit/Cost). The internal return rate (IRR) and the net present value (NPV) are other methods that have been used. The use of NPV application was also found in BCA.

Much of the available literature on risk mitigation measures have been applied in developed countries. Lund (2002) analyzed the implications of flood risk reduction measures, such as the use of levees, sandbags, among others including how potential losses are reduced using an optimization metric. However, some risk mitigation measures adopted in developing countries may be mistakenly classified as a subset of techniques applied in more developed countries due to insufficient institutional capacity to manage data and information.

Rose et al. (2007) analyzed the Benefit/Cost (B/C) ratio of the mitigation subsidy provided by the USA’s Federal Emergency Management Agency (FEMA), where a B/C ratio larger than 1.0 was found for all the considered hazards.

Rose et al. (2007) also highlighted the total benefits of FEMA’s hazard and risk mitigation program, between 1993 and 2003 that were US$14 billion, which compare to the US$3.5 billion of implementation costs, yielding a B/C ratio of 4.0. The mitigation benefits included improvements in public safety, the implementation of projects to prevent a given number of fatalities and injuries during the lifetime of the mitigation works and the estimation of the NPV for investments in mitigation measures related to flood, wind and earthquake hazards.

Another example of a BCA in a developed country (Japan) was summarized by Fujimi (2012). The study analyzes whether a financial guarantee for seismic retrofitting of existing structures should be considered. From an economic perspective, this can be more efficient, than a *post*-event subsidy, even if the costs associated to the guarantee are overestimated. Under this program, the government is responsible for all material losses caused by earthquakes, provided that the homeowner has implemented standards (e.g. building code) for risk mitigation measures. Fujimi (2012) case study identified an additional success indicator. Homeowners who join the program, enjoy additional benefits in the form of an increase in property value compared to those whodid not participate in the program.

The literature reviewed on developing countries addresses different analysis metrics that are generally prepared for specific assets and hazards. This is important because the types of risk mitigation measures and their efficiency are not necessarily comparable with other assets or hazards (e.g., analyzing risk mitigation measures for a house located within a floodplain with particular characteristics at a given location; comparing the outcomes with the available results in the literature reviewed for a house in the State of Florida in the USA; or a province in Japan that has been subject to structural retrofitting for hurricanes or earthquakes, respectively). The methodologies to analyze hazards and perform an appraisal of exposure in these two locations are hardly applicable to least developed countries.

In general, literature related to this instrument can be simplified in the following analytical expression, which is composed of the following components: Mitigation Investment (*MI*) defined as the functional relationship between the possible future Damage Reduction (*DR*) and the necessary cost to implement measures for Risk Reduction (*RR*).

$$MI = f(DR, RR) \qquad (2\text{-}6)$$

Pereira (1995) analyzed risk mitigation measures for different types of buildings in Jamaica. The study made use of incremental costs and benefits,the latter is obtained *ex-post*. Ghesquiere et al. (2006) performed an analysis of different options of risk mitigation measures for several types of buildings (classified by sector) with and without structural retrofitting.

Benson and Twigg (2004) developed one of the most complete economic analyzes available to date - several dimensions of the risk mitigation process were evaluated. The study included a timeline of risk mitigation analyses, proposing specific methods to determine their net benefits.

Mechler (2004) showed an analysis in the form of guidelines, where flood risk was estimated in Piura, Peru. Events with 10, 50, 100 and 200 years of return period were considered. For the 100-year return period, the estimated losses were approximately US$496 million[5].

Kenny (2012) concluded that retrofitting costs can vary significantly depending on the characteristics of a building and its location. The probability that a large earthquake may cause large damages and losses, has to do with the location of the asset under analysis and therefore, is surrounded by uncertainty. In other words, there are many variables that can determine if a building is at risk of collapse, as for instance hazard intensity level, the

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[5] Based on https://www1.oanda.com/currency/converter/ (November 28, 2019).

structural system, the construction materials and the design and construction standards that were used.

Michel-Kerjan et al. (2013) performed one of the most innovative studies, using high resolution models or probabilistic loss estimates to quantify the benefits of risk mitigation investments. This study evaluated the B/C ratio of risk mitigation measures in two developing countries. It is relevant to note that authors implement an analysis and risk assessment using expression (2-2) to measure the risk variations, with and without the risk mitigation measure, using a B/C ratio metric over a functional relationship of the risk curve. In the risk mitigation literature, this is one of the most innovative and rigorous analyzes in its application.

2.4 RISK RETENTION AND TRANSFER

Risk retention and transfer is currently perhaps the least studied field on disaster risk management in developing countries.

In the 1990s, some developing countries implemented risk retention strategies by creating calamity funds, which served as national self-funding schemes with the objective of having monetary reserves to be used when incurring losses caused by catastrophic events.

Risk retention and transfer instruments require financial support from governments (at least in the beginning) and can be classified into two main categories:

i. Those backed up by mandatory public or private insurance instruments, with or without a subsidy, that feed the scheme, and,
ii. those that are not backed by an explicit insurance instrument but provide governments with funds to be spent in the aftermath of a disaster.

Some examples of the first type of schemes are found in developed countries, such as the Insurance Compensation Consortium of Spain; the earthquake and hurricane funds in the States of California and Florida, respectively; the Central Bank for Reinsurance in France; the Japan Earthquake Reinsurance Company and the Natural Disaster Fund of New Zealand. The second type of schemes are mostly found in developing countries and some examples are the Natural Disaster Fund of Mexico (FONDEN for its acronym in Spanish), the Turkish Catastrophe Insurance Pool (TCIP) and the Natural Disaster Insurance Pool (PAID) in Romania.

The functional form that describes a risk retention strategy is summarized in equation (2-7), which describes the protection generated by the capital accumulation (savings in the form of self-protection). A typical form that this savings can take is the establishment of a fund, which has also an associated cost. Therefore, financing retention, *FR*, through a retention fund is a function of two fundamental variables: the amount of own capital (savings), *OC*, and its cost, *C*.

$$FR = f(OC, C) \qquad (2\text{-}7)$$

The opportunity cost of such resources is usually very high, particularly because it prevents governments from investing in other social needs, which is evident mainly in developing countries.

The theoretical concept of self-protection is not new. Becker and Ehrlich (1972) analyze the viability of the self-insurance (loss taking) and self-protection (risk taking) markets and concluded that, for certain price conditions, market insurance and the self-insurance are to be substitutes, whereas market insurance and self-protection can be complements. It should be recognized that self-insurance is a mechanism that allows financing losses by assuming them, whereas self-protection influences the risk occurrence probabilities. This analysis challenges the notion that moral hazard is an unavoidable consequence of any market insurance, by showing that under certain conditions, it may lead to a decrease of the risk probabilities. For example, in the context of a medical insurance, self-insurance could be a way to save resources to cover higher deductibles, whereas self-protection could be an increase of the medical controls and start of healthy activities and routines, which can reduce the risk occurrence probability.

Barnichon (2008) performs a specific analysis for developing countries, related to the use of international reserves and self-insurance to manage external shocks. The study focuses on small economies and besides disasters, it also considers external commercial shocks. Along the same research line, Ogaki et al. (1996) and Jeanne and Ranciere (2006) analyzed the optimal size for a fund to be used as a self-insurance instrument.

Finally, Lester (2009) performed a market analysis for the insurance and reinsurance sectors from the perspective of economic rationality, finding that a risk retention approach is a synonym for efficient risk management. In this sense, risk retention is not only considered as a financial instrument, but as a comprehensive approach since it includes other factors such as loss control and risk avoidance. For the public-sector case, it is also possible to use taxes to finance frequent losses or those that because of their nature, a reinsurer and insurer does not take (or for which if coverage is available, is very expensive).

In the reviewed literature, risk transfer has been found in two different operational forms. Both forms provide contingent capital and can acquire the form of insurance or debt (understanding debt as a type of risk transfer). In the function for risk transfer, *T*, in both debt and insurance forms, contingent capital, *C*, is obtained to manage losses, and there is also an associated cost, *Ct*, to each transferred unit. Expression (2-8) shows the functional relationship of the amount to be transferred, as a function of the capital for protection.

$$T = f(C, Ct) \tag{2-8}$$

When risk is transferred to a third party, the operation takes the form of a traditional insurance instrument. The cost associated to this type of instrument is denoted as a premium, and the received capital is not returned to whom the risk was transferred to. When it comes to risk financing over time, the contingent capital source takes the form of a debt, which must be paid in full, and the cost associated with the risk transfer is known as a coupon. It is often mistakenly considered that insurance is not like a debt, because it must be paid in full, whereas insurance only requires the payment of an annual premium. If the technical (or fair) premium is paid during a large enough timeframe, the averaged losses will tend to be paid by the annual payment of such value. In summary, debt and insurance instruments differ only in the funding sources. In the first one the lenders provide the capital whereas in the second one, shareholders of the insurance company provide it.

Regarding risk transfer to third parties, the insurance market and its associated products have been the main topics of analyses by different researchers. Over the past two decades, there has been a steady increase of risk transfer strategies in the form of insurance instruments, particularly in developing countries, where the insurance penetration rate has been historically low. According to Cummins et al. (2009), in these developing countries the following types of risk financing mechanisms are available: 1) sovereign risk, 2) property risk, 3) agricultural risk and, 4) micro-insurance.

As an example, the Climate-Wise database, developed by the University of Cambridge, included (at the end of 2014) approximately 125 insurance-related initiatives that provide coverage related to natural hazards, all of them consistent with the approach mentioned by Cummins et al. (2009).

Gurenko et al. (2004) summarized different research initiatives on catastrophe reinsurance. As an example, Castaldi (2004), explained the benefits of specific forms of risk transfer to third parties between reinsurers, known as retrocession, distinguishing it from alternative schemes that make use of capital markets, such as catastrophe bonds (CAT bonds). Nicholson (2004) analyzed the case of the reinsurance scheme of the Florida Hurricane Catastrophe Fund, whereas Vallet (2004) performed a similar analysis for the Central Reinsurance Fund in France. Von Lucius (2004) described the Turkish Natural Catastrophe Insurance Pool scheme and Takeda (2004) provided details on the experience in Japan in this field. Finally, Lane (2004) proposed a way to price CAT bonds to transfer risk in developing countries, Ibarra (2004) analyzed the case of funds for agricultural insurance in Mexico and Lacey (2004) highlighted the key factors to analyze risk coverage for the population living under poverty conditions.

The finding of the literature review show that risk transfer to third parties is the field with most financial innovation. The examples of Mexico’s CAT bonds, followed by Turkey, and the schemes designed for the Caribbean support this statement. A key aspect in the development of these instruments is that the technology used in developing countries was originally thought to be used by insurers and reinsurers for their own risk management activities (Lane, 2002). Lane (2002) produced an encyclopedia with state-of-the-art risk management schemes, all developed during the last decade, that have represented milestones. A common language is proposed to analyze risk mitigation and risk transfer instruments to third parties (e.g., insurance, reinsurance, retrocession, and securitization of risk over time) considering their different dimensions, such as valuation techniques and the development and appraisal of risk portfolios. Even if these schemes were innovative approaches in the reinsurance industry at the time, currently these are the standard models that are being used in developing countries.

The innovations that have developed in the field of disaster risk transfer to third parties make financial protection comprehensive. Banks (2004) shows the risk management instruments not individually but grouped and evaluates them using a BCA. Nevertheless, it should be noted that the risk portfolio has a value, reason why the individual and grouped analyses of the instruments are relevant. This finding by Banks (2004) is important for disaster risk management in developing countries because the trend indicates that the analytical approach should be used.

Finally, Briys-De-Varenne (2001) provided a revealing analysis on the convergence between the insurance industry and the capital markets. This approach is considered innovative because standard models used to consider disaster risk financing through its retention with reserves and insurance only. However, supported in the above-mentioned convergence, the menu of financial alternatives broadens by not only having at hand the capital provided by insurers and reinsurers but also the one owned by public investors who participate in capital markets.

The literature on risk transfer is even broader when it is limited only to establishing its conceptual and/or theoretical feasibility. The works by Andersen (2002), Andersen et al. (2005) and particularly Andersen et al. (2010), carried out descriptive approaches on risk management concepts for developing countries to evaluate both, the instruments and their implementation potential.

It should be noted that most of the available literature on risk transfer does not illustrate the design of complete portfolios for financial instruments in disaster risk management. This is reflected in a lack of decision-making methods to design strategies that combine different instruments where all layers of disaster risk are managed – in addition to having a methodology to compare instruments available - so that a criterion can be established to assess the efficiency of an instrument if compared with another, or to extend the analysis to portfolios of instruments and compare them. In summary, this is the representative approach used to analyze risk transfer in developing countries.

Risk transfer over time (including contingent debts) has been widely studied[6] because several multilateral and even commercial banks have offered lines of credit (LoC) linked to disasters. These credits finance the losses incurred by governments, and the product of the credit contributes to finance the different aspects of the disasters. This transfer is occurring over time because the credit transfers public expenditure from the future to the present.

2.5 COMPREHENSIVE DISASTER RISK MANAGEMENT

This document defines comprehensive disaster risk management as a theoretical approach, where the public budget for risk mitigation investment is managed, for both, *ex-ante* risk mitigation measures and *ex-post* expenses (i.e. those needed in the aftermath of an event), including both low-frequency/high-intensity events and high-frequency/ low-intensity ones.

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[6] This type of instrument is highlighted as a feasible option in Freeman et al. (2003), Hofman and Brukoff (2006) and Rassmussen (2004).

The functional form that summarizes the findings of the reviewed literature is shown in expression (2-9), where the instruments for managing risk mitigation, retention (both in the form of reserves and debt) and risk transfer actions are considered (i.e., expressions (2-6), (2-7) and (2-8)).

$$G = G(FR, MI, T) \qquad (2\text{-}9)$$

In this case, a description of risk[7] is needed (2-2) to estimate L. Once L is determined using a probabilistic approach, it is then possible to obtain return periods or exceedance probabilities for different loss values and thereby, identify different risk layers (those where risk mitigation, retention and transfer can be used) for an efficient management. Within specialized risk markets, each of these layers could belong to a market, so that a comprehensive disaster risk management strategy is able to assign to each layer a specific risk financing instrument.

The field of literature that covers the applications in developing countries is the one where the larger conceptual progress exists. Nevertheless, it is also where the empirical applications face the biggest challenges and the least advances. In summary, the conversion of expression (2-9) into concrete analysis models that allow defining different risk layers remains a challenge.

Risk layering is also a well-studied field by insurers and reinsurers; particularly on stratifying risk by assigning specific risk transfer instruments to each layer. However, in the literature on comprehensive disaster risk management for developing countries, it is still considered as an innovative subject (Ghesquiere and Mahul, 2007).

Regarding the available models in literature for risk layering, Luyang and Khury (2010) used a mean-variance model to obtain optimal allocations by layer for various types of reinsurance contracts. Venter (2001) made a proposal focused to insurance companies, where the costs are estimated by considering different insurance options and the different layers for the reinsurance contracts. Niehaus (2002) developed a theoretical and analytical approach to assess how to share the risk and estimate the optimal reinsurance allocation, considering the governmental participation in its distribution between the economic agents. Risk layering has a key role when defining catastrophe risk financing options. Wang et al. (2014) proposed a dynamical optimization model for risk layering, able to solve a common

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[7] In the following chapters we will define an empirical functional form that summarizes this expression using a LEC.

problem between insurers and reinsurers, by assigning contracts to different layers according to the characteristics of the reinsurance contract used in each of them.

Mutenga and Staikouras (2007) proposed a theory on disaster risk financing using the different available instruments in the insurance and reinsurance markets, besides providing arguments to indicate that each of these instruments can be assigned within a layered structure. Authors found that one of the variables to consider when performing a risk layering process by tool, is the cost of capital and the insurer's ability to cope with extreme events with capital of its own. Boyer et al. (2011) proposed a model of minimum marginal costs to determine the layer limits in catastrophe risk transfer schemes between reinsurers, being this a similar methodology to the proposed by Gurenko and Mahul (2003) to be applied in developing countries.

Gurenko and Mahul (2003; 2006) made a proposal based on the use of widely used concepts in the insurance and reinsurance industry, but now applied to governments in developing countries. The authors proposed a portfolio of comprehensive disaster risk management instruments, together with a set of decision rules, to choose the amounts of layered risk structures and their associated costs by applying a minimum marginal cost approach. It should be noted that the investments in risk mitigation are not included in this analysis, the reserves are considered only as risk retention instruments and debt and insurance are used as financial instruments for emergency response, recovery and reconstruction in the aftermath of a disaster.

Expression (2-9) summarizes a comprehensive disaster risk management strategy, which is the field where the biggest challenges exist in developing countries; particularly when the description of risk is made in terms of expression (2-2) (i.e. risk assessments with a high-resolution level and probabilistic approaches, because of a lack of data to feed the models). The literature in this field is still limited, in part because of the few analyses available on which instruments to use, how to use them and compare them with consistent and homogeneous metrics.

A robust methodology or model, that combines risk mitigation, risk retention (in the form of reserves and debt) and risk transfer strategies, within the same decision-making process, and that proposes optimal allocations to risk layers – in addition to considering budgetary constraints and inter-temporalities- has not yet been developed. The only existing study that addresses some of these needs is the one developed by Hochrainer (2014), where the methodology used by the Catastrophe Simulation Model (CATSIM) tool is described. The model by Hochrainer (2014) can analyze the fiscal vulnerability of a country to disasters and assess the effect of using financial instruments to close the potential gap in public balances. However, the optimization process between instruments proposed by CATSIM does not consider the mitigation layer in the optimization analysis since it is treated as an exogenous variable. Because of that, the model does not optimize the structure for the risk layers.

Additional detailed studies are needed to support the last statement. The United Nations Framework Convention on Climate Change (UNFCCC, 2012) has summaries of the available methodologies to assess and quantify damages and losses associated to climate change. Within these studies, several models and methodologies were analyzed such as: 1) CATSIM, 2) CAPRA, 3) Integrated Assessment Models (IAMs) or models that study the interaction between economic and climate systems, 4) scenario analysis, 5) The approach to assess climate change risk by the Department for Environment, Food and Rural Affairs of the United Kingdom and, 6) The Global Risk Index. Each of these models incorporate a specific perspective on climate change and its impacts for different stakeholders. However, none of these models allows performing risk layered analyses, where the optimal allocation of the resources is based on the specific risk characteristics and at the same time considers budgetary restraints and inter-temporal analyses.

The methodology proposed in the following chapter has as an objective to include all the components of expression (2-9), using the outcomes from studies developed under the conceptual framework of expression (2-2). The methodology seeks to fill the above-mentioned research gaps by developing a model that allows comparing comprehensive disaster risk management strategies that not only combine financial instruments but also consider investments in different types of risk mitigation measures. By using this model, it is demonstrated that it is possible to make optimal decisions, even between different portfolios of instruments, thereby determining the efficiency of each instrument and the one of the analyzed portfolio, in light of its optimal contribution to finance L (see expression 2-3).

3 THE MODEL

In this section, a theoretical methodology or model is developed to select the best possible composition among four possible actions based on the conceptual framework of a comprehensive disaster risk management strategy: a) investment in risk mitigation measures (mostly in the form of structural retrofitting), b) creation of a reserve fund to cover a share of the feasible future losses, c) engagement in a contingent debt instrument to finance the feasible future losses and, d) purchase of insurance coverage to transfer a portion of the feasible future losses to a specialized third party. Each possible composition or strategy as defined in this section, represents a series of costs and benefits that allow comparisons between them and choose the best one, (i.e. the option that yields the highest ratio between benefits and costs, either subject to a budgetary constraint, or not). As discussed in the previous chapter, this approach can be considered as the most robust to date. In the absence of a comprehensive theoretical framework among the available models, it is adequate to compare *ex-ante* risk mitigation measures with *ex-post* financing strategies (including reserve funds, debt and insurance instruments).

The first section of this chapter provides the theoretical bases that allow to establish optimal compositions by comparing the efficiency of risk mitigation investment measures against those of *ex-post* financing schemes (risk retention and transfer). The decision-maker can compare the incidence of each action in the net expected loss, besides knowing their benefits and costs, so that the action (or combination of actions) that yields the highest ratio (after explicitly considering the costs and budgetary conditions) can be chosen. The second section of this chapter describes a BCA for different cases. The third section provides details on how the model can be used by a decision-maker in establishing a hierarchical decision process, which is applicable only for those who make decisions in favor of a group of sectors or socio-political regions. Finally, there is an Annex that discusses how to approximate its BCA in different mitigation options.

3.1 DEFINITION OF RISK AND ACTIONS THAT HAVE AN IMPACT ON IT

3.1.1 Estimating the loss exceedance curve, exceedance rate and average annual loss

What most probabilistic estimation models calculate are the exceedance probabilities within a given timeframe for different loss values, l_i. When these data are shown in a graphical manner (pairs of li and their exceedance probabilities, $\Pr(L_i > l_i)$), an EP curve is obtained, as schematically shown in Figure 1.

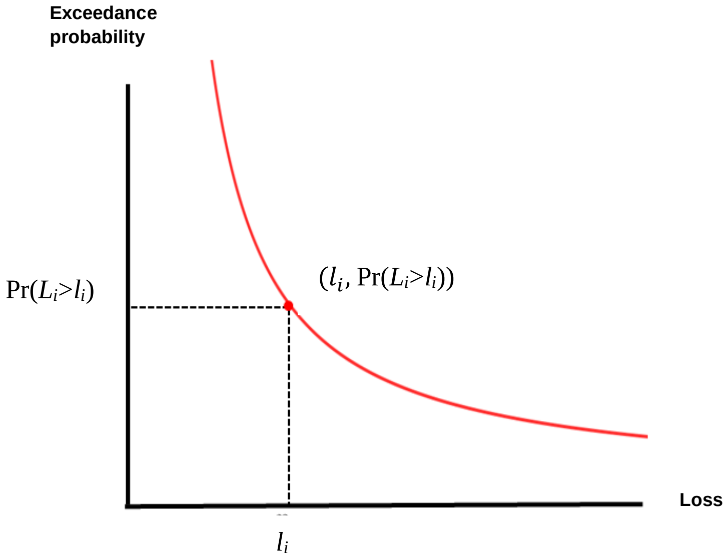


Figure 1. Schematic representation of an EP curve.

For any arbitrarily defined l_i value, the loss exceedance probability, regardless the event that caused it, can be estimated as:

$$Exceedance\ probability\ of\ \ l_i = \frac{number\ of\ losses\ higher\ than\ l_i}{total\ number\ of\ losses} \tag{3-1}$$

Losses, in this context, are conditional to the occurrence of a natural hazard and for this reason, the total probability theorem becomes useful. This theorem allows to estimate the occurrence probability of any event, *B*, from its conditional probabilities. In mathematical terms, this can be expressed as follows:

$$\Pr(B) = \sum_{i=1}^{N} \Pr(B|A_i) * \Pr\,(A_i) \tag{3-2}$$

In this case, event *B* represents the fact that the loss exceeds a certain value, l, and is conditional to the occurrence of a natural event. Rearranging the total probability theorem with the variables of interest herein, and applying it to the continuous case, the following expression is obtained:

$$Pr(L_i > l_i) = \int_i^N Pr(L_i > l_i | event_i) * Pr(event_i)\, di \qquad (3\text{-}3)$$

where *N* is the total number of events that caused losses in the considered timeframe (e.g., 50 years).

Besides exceedance probabilities, exceedance rates (i.e. the average number of times that losses exceed a l_i value) can be obtained too. This is useful since for many applications, rates are easier to handle and understand than probabilities and these two concepts are closely related as shown in the following expressions:

$$v(l) = \int_i^N Pr(L_i > l_i | event_i) * (event\ frequency_i)\, di \qquad (3\text{-}4)$$

$$v(l) = \int_i^N Pr(L_i > l_i | event_i) * (event\ frequency_i) * \left(\frac{N}{N}\right) di \qquad (3\text{-}5)$$

$$v(l) = N * \int_i^N Pr(L_i > l_i | event_i) * Pr(event_i)\, di \qquad (3\text{-}6)$$

$$v(l) = N * Pr(L_i > l_i) \qquad (3\text{-}7)$$

When exceedance rates are estimated for several loss values, data can also be presented in a graphical manner, as shown in Figure 2, to generate what is known as the loss exceedance curve (LEC), which although is based on the same data as the EP curve, provides the result in a different metric.

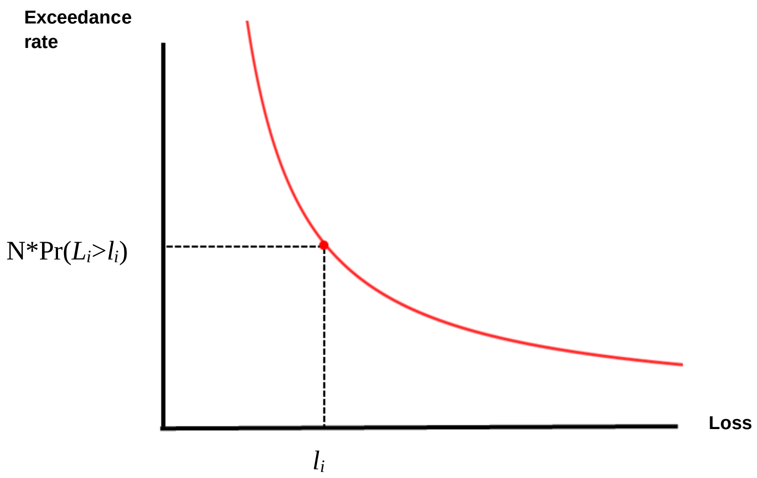


Figure 2. Schematic representation of a LEC.

Finally, another widely used risk metric is the Average Annual Loss (AAL), which corresponds to the annualized and averaged expected value of future losses, associated to a set of events that occur over a long enough timeframe, which has the following mathematical expression:

$$E\,[\sum_i L_i * fi] = \sum_i E[L_i] * fi \qquad (3\text{-}8)$$

where *fi* indicates the occurrence frequency of each event. The AAL can also be obtained after integrating the LEC. The integration of $v(l) = N * Pr(L_i > l_i)$ takes the following form:

$$AAL = \int_{l=0}^{l=exposed\ value} v(l)dl = N\int_{l_i=0}^{l_i=exposed\ value} \Pr(L_i > l)dl_i \qquad (3\text{-}9)$$

It is also necessary to highlight a couple of preventive notes about the meaning of L_i in the context of the present model and its applications at country level. The first one being that public-sector losses depend on how each government defines its social responsibility with respect to damage and losses caused by disasters. Models such as CATSIM, or Mexico's experience with FONDEN (2012) demonstrate that a unique rule, or regulatory framework that is commonly accepted to define the governmental responsibilities in the event of a disaster does not exist. While some countries would allocate public resources exclusively to cover the cost of the emergency attention and the reconstruction and recovery processes of public infrastructure, other governments would cover private losses under certain approved regulations. Governments in many countries have also discretionary power to define when the allocation of public resources can take place. For this reason, in the context of this model, L_i is a generic concept that should be specifically adapted to each case study.

The second note is related to the economic, political and social value that each country assigns to L_i when estimated through probabilistic models. As explained before, the value of L_i is obtained from engineering models that estimate the replacement cost of the damaged assets by a specific event. This value does not necessarily match with the societal value that a country can assign to them, given the applicable risk tolerance function. The implication of this would be that a "risk-tolerant" country would assign a discounted value to L_i, a "risk-neutral" country would assign L_i the exact same value of the technical estimation and a “risk-averse” country would assign a lower value to L_i to reflect its lower risk tolerance.

Since disaster risk tolerance is not defined or agreed internationally, to b able to influence a country risk tolerance function on this model, the risk-neutrality attitude of governments proposed by Mahul and Gurenko (2006) is used. If the methodology is applied to cases in which there are well-defined parameters, either in the form of legislation or of functions that allow defining the risk tolerance function of a country, the user of the model is required to adjust the corresponding premiums or discounts in an exogenous way.

3.1.2 Conceptual analysis of risk mitigation measures in the LEC: a first approximation

One of the main actions a country can take to reduce disaster risk is to invest in risk mitigation measures. These measures are those that can reduce the potential damage and losses in the event of a disaster. To assess the effectiveness of these risk mitigation measures, it is first necessary to assess the variations on the LEC after their implementation. Next, an estimation of the impact of a risk mitigation measure is analyzed to understand its contribution, as a potential decrease of the AAL.

The example used in this section considers a percentage reduction of the AAL, which is defined as $1-\propto_j$, (i.e. the percentage of damage and loss reduction because of implementing a risk mitigation measure is equal to the difference between the initial AAL and the one estimated after its implementation).

To consider the variation of the possible losses mentioned above, it is necessary to bear in mind that the initial loss, without any risk mitigation measure, is defined as L_i, whereas the expected loss after the implementation of a risk mitigation measure is defined as $L_i' = \alpha_j * L_i$. It is also important to remember that $0 \leq \alpha_j \leq 1$, where j represents the type of risk mitigation measure implemented, which in this model can have three levels of risk reduction: low (*lo*), medium (*m*) or high (*hi*). In general, a risk mitigation measure classified as high will reduce more damages and losses than the other types of measures (while more financial resources would be required for its implementation), therefore, the relationship between these damage percentages is:

$$\alpha_{\mathrm{hi}} < \alpha_{\mathrm{m}} < \alpha_{\mathrm{lo}} \tag{3-10}$$

$$1 - \alpha_{\mathrm{lo}} < 1 - \alpha_{\mathrm{m}} < 1 - \alpha_{\mathrm{hi}} \tag{3-11}$$

In the previous section, the exceedance probability of a certain loss level, l_i, was defined as $Pr(L_i > l)$. The implementation of a risk mitigation measure modifies the value of the loss variation. Therefore, a similar expression is obtained through the following expressions for estimating the new loss exceedance probability:

$$Pr(L_i{}' > l_i) = \int_i^N Pr(L_i{}' > l | event_i) * Pr(event_i)\, di \tag{3-12}$$

$$Pr(L_i{}' > l_i) = \int_i^N Pr\big(\alpha_j * L_i > l_i | event_i\big) * Pr(event_i)\, di \tag{3-13}$$

$$Pr(L_i{}' > l_i) = \int_i^N Pr\left(L_i > \frac{l_i}{\alpha_j} | event_i\right) * Pr(event_i)\, di \tag{3-14}$$

$$Pr(L_i{}' > l_i) = \mathrm{Pr}\left(L_i > \frac{l_i}{\alpha_j}\right) \tag{3-15}$$

As defined in the previous paragraph, $0 \leq \alpha_j \leq 1$, so that the value of loss $\frac{l_i}{\alpha_j}$ is always higher than l_i, meaning that the exceedance probability of a specific loss value, once a risk mitigation measure is implemented, is equivalent to the exceedance probability of a higher loss which is consistent with the initial LEC, as shown in Figure 3.

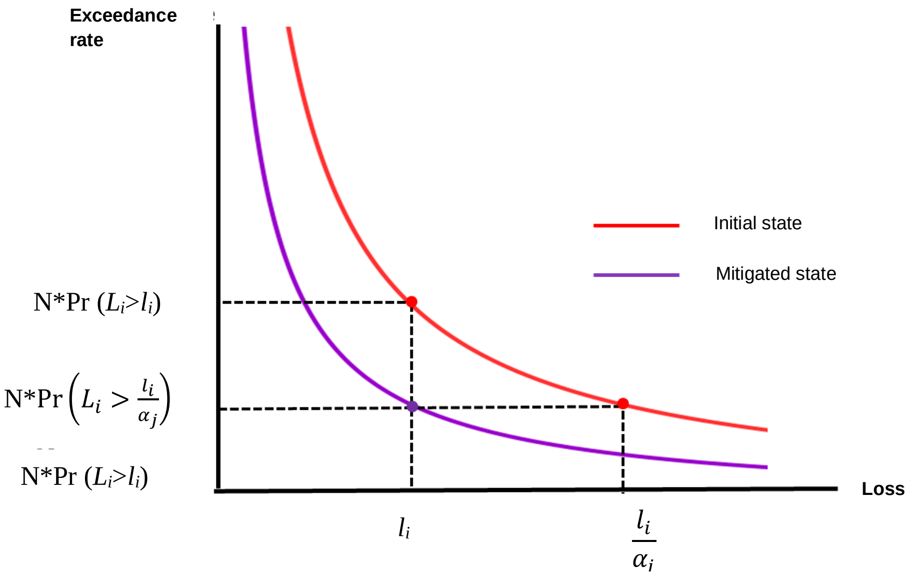


Figure 3. Displacement of the LEC because of implementing a mitigation measure.

The above-example is a particular case of a risk mitigation measure that affects all rates and probabilities of losses of a particular LEC. It is also possible that there are risk mitigation measures that only affect a part of the LEC. For instance, if a dike is built with the aim of mitigating flood risk, it will provide protection up to a certain hazard level, so the mitigated state LEC, instead of having a parallel displacement with respect of the one in the initial state, as shown in Figure 3, could have the variations only around a certain incidence range, or even have a non-linear variation.

The lineal AAL variation example can also be used to illustrate the effects of risk mitigation measures because, using this approach, besides the quantification of risk reduction by estimating the differences between two LEC, the AAL, with and without the implementation of the risk mitigation measure, can also be calculated.

For that purpose, the initial LEC should be integrated:

$$\int_{l=0}^{l=exposed\ value} v(l)dl = N\int_{l_i=0}^{l_i=exposed\ value} \Pr(L_i > l_i)dl_i \qquad (3\text{-}16)$$

However, the LEC obtained after considering the implementation of the risk mitigation measure is also integrated:

$$\int_{l=0}^{l=exposed\ value} v(l')dl = N\int_{l_i'=0}^{l'=exposedvalue} \Pr(L_i{}' > l_i)dl_i \qquad (3\text{-}17)$$

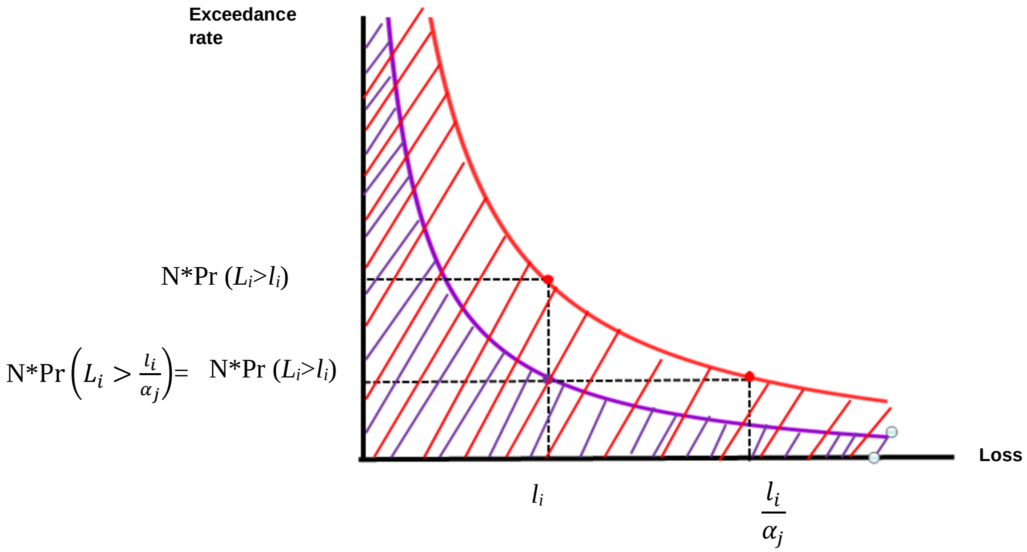


Figure 4. Comparison of the AAL between two LEC (initial and mitigated states).

The area in red in Figure 4 corresponds to the AAL in the initial state (without any risk mitigation measures), whereas the purple area corresponds to the AAL after the implementation of a risk mitigation measure. It is evident that area in red is larger than area in purple, implying that the initial AAL is higher. This also means that there is a benefit associated to the risk mitigation measure, which equals the savings generated by it, in terms of the AAL. Therefore, the benefits can be represented by the following mathematical expression, depicted as the blue area in Figure 5.

$$B(mitigation) = \int_{l=0}^{l=exposed\ value} v(l)dl - \int_{l\prime=0}^{lr=exposedvalue} v(l')dl' \qquad (3\text{-}18)$$

$$= N\int_{l_i=0}^{l_i=exposed\ value} \Pr(L_i > l_i)dl_i - N\int_{\mathrm{l_i}\prime=0}^{\mathrm{l_i'}=\mathrm{exposedvalue}} \Pr(L_i' > l_i)dl_i \qquad (3\text{-}19)$$

$$= N\int_{l_i=0}^{l_i=exposed\ value} Pr(L_i > l_i)dl_i - N\int_{l_i=0}^{l_i=exposed\ value} \Pr\left(L_i > \frac{l_i}{\alpha_j}\right)dl \qquad (3\text{-}20)$$

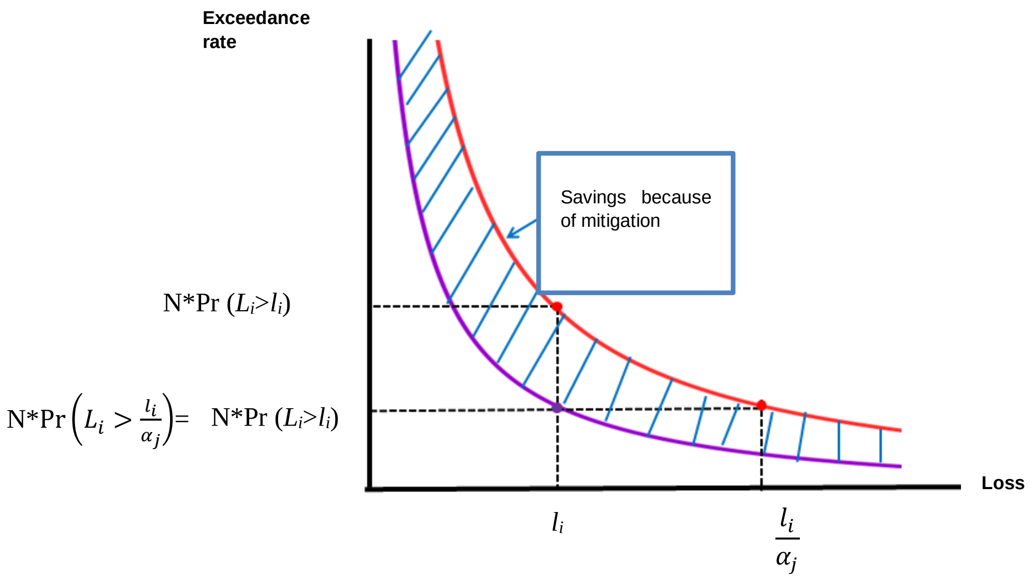


Figure 5. Benefit associated to a risk mitigation measure.

The impact of a risk mitigation measure has been considered as a percentage ratio equivalent to $1-\propto_{j}$. This percentage provides a metric of the displacement that occurs between the two risk curves as shown in Figure 5. In other words, a higher percentage represents a higher displacement between the initial and mitigated state LECs, which at the same time represents a higher loss reduction and therefore greater effectiveness of the risk mitigation measure, despite requiring more financial resources.

The example above was only illustrative and serves as an introduction to some key concepts about disaster risk mitigation. The required structural changes for the implementation of a risk mitigation measure in infrastructure can encompass a wide range of typologies. Because of this, the feasibility studies must consider a set of complex structural engineering variables that should be assessed for each hazard. In other words, to achieve a specific percentage reduction, $1-\propto_{j}$, a detailed analysis is usually required.

Another possible way to describe the problem mentioned above is through the net losses (N_L) which a decision-maker faces once a risk mitigation measure is implemented. These are equal to the gross losses (G_L) of the initial state (without any risk mitigation measure) minus the benefits provided by mitigation, *B* (*mitigation*). In a broad sense, by comparing the LEC of the initial and mitigated states, some important interdependencies related to the use of financial tools, for both risk retention (through reserves and debt) and transfer, become evident. This is because any investment in risk mitigation yields a reduction in the

AAL and as explained later in more detail, the lower the AAL, the lower the demand for disaster financing instruments. That is, the first stage is to identify the benefits that can be achieved by governments that invest in disaster risk mitigation, followed by defining how risk retention (through reserves and debt) and transfer activities can be used to manage the residual risk.

3.1.3 The benefits of financial instruments: two approaches

The definition of a benefit in disaster risk mitigation is broad. A typical example of a benefit could be the reduction of the expected losses. This model proposes that the benefits associated to the strategies correspond to the differences in value over time between gross and net losses, after implementing a strategy.

This section shows an alternative way of quantifying the benefits of the financial instruments through the estimation of the difference between the present values of the gross and net losses. The gross loss corresponds to the one a decision maker is responsible for when no risk mitigation strategy exists (initial state). The net loss corresponds to the remaining amount that the decision-maker is responsible for once the risk mitigation strategy has absorbed a share of the gross loss.

To explain this approach, it is necessary to assume that losses caused by disasters follow a stochastic process over time, where the occurrence times and loss amounts are random values.

The relationship between the probability density function of losses and its exceedance rates is the following:

$$f_l(l) = -\frac{1}{N}\frac{d}{dl}v(l) \tag{3-21}$$

Regarding the occurrence over time, it can be assumed that the occurrence of disasters follows a Poisson process. In this example, the time between disasters is assumed as independent and follows an exponential distribution with parameter $\beta = \left(\frac{1}{N}\right)$. If so, the time to the i^{th} disaster follows the following Gamma distribution:

$$f_i(t_i) = \frac{t_i^{i-1} e^{-Nt_i} N^i}{\Gamma(i)} \tag{3-22}$$

Similarly, it is assumed that loss values and occurrence times are not correlated. Given the above, the present value of future gross losses can be calculated using the following expression:

$$L = \sum_{i=1}^{\infty} L_i e^{-\partial t_i} \qquad (3\text{-}23)$$

where L_i is the loss caused by the i^{th} disaster, which occurred at time t_i and ∂ is the discount rate used to account for the value of money over time.

The present value of future net losses is calculated as:

$$L^N = \sum_{i=1}^{\infty} L_i^N e^{-\partial t_i} \qquad (3\text{-}24)$$

Where L_i^N is the net loss caused by the i^{th} disaster, which occurred at time t_i and again, ∂ is the discount rate used to consider the value of money over time. Besides this, the net loss that a decision-maker is responsible for in the loss interval, $[l_k, l_{k+1}]$, when engaging in a financial instrument is:

$$L^N = \begin{cases} L_B & if\ \ L_B < l_k \\ l_k & if\ \ l_k \leq P_B \leq l_{k+1} \\ P_B - (l_{k+1} - l_k) & if\ \ l_{k+1} < L_B \end{cases}$$

(3-25)

where L_B corresponds to the gross loss.

Given the above, the benefit of the financial instrument, according to approach B, is defined as follows:

$$Benefit\ of\ the\ instrument = E\left[\sum_{i=1}^{\infty} l_{iB} * e^{-\partial t_i}\right] - E\left[\sum_{i=1}^{\infty} l_i{}^N * e^{-\partial t_i}\right] = E\left[\sum_{i=1}^{\infty} l_{iB} * e^{-\partial t_i} - l_i^N * e^{-\partial t_i}\right] = E[L] - E[L^N] \qquad (3\text{-}26)$$

E$[L_i]$ and $E[L_i^N]$ were replaced by $E[L]$ and $E[L^N]$ respectively, given that all $L\'s$ and $L_i^N\'s$ are identically distributed and are not correlated with t_i.

Taking in consideration the previous sections of this chapter, an economic model is presented in the following section to allow decision-makers to optimize the combination of disaster financing instruments that yield the highest benefit per monetary unit to be spent in the event of a disaster.

The model should be robust and useful to decision-makers because it explicitly considers the value of losses over time by means of a discount rate.

3.2 BENEFIT/COST ANALYSIS

The proposed methodology uses a BCA for which a country makes decisions on the convenience of investing in a determined *strategy* (e.g., combining a risk mitigation measure with the purchase of insurance coverage for a given range of losses) to reduce the burden of losses caused by disasters. To rank between instruments, the BCA follows these stages:

1. Identification of risk mitigation measures (or *ex-ante* investment) and financial instruments (*ex-post*) applicable to the area under study.
2. Identification of a set of possible strategies, $S = (s_1, s_2, \dots, s_i)$, that result as a combination of risk mitigation measures and financial instruments.
3. Identification of the costs and benefits related to each strategy.
4. Quantification of costs and benefits over time.
5. Comparison of the flows for costs and benefits through a B/C relationship, defined as: $\frac{B}{C} = \frac{Present\ value\ of\ the\ benefits}{Present\ value\ of\ the\ costs}$.
6. Selection of the optimal strategy.

The following sections provide details of the BCA used in this model.

The model allows stratifying risk into four layers:

i. That one subject to risk mitigation (with structural measures as per the scope of this study),
ii. that one subject to retention (including reserve funds and contingent debt),
iii. that one subject to be transferred and,
iv. that one where no mitigation actions are envisaged.

The model defines and measures the benefits of these strategies by quantifying the variations over the LEC. However, the methodology also incorporates appraisal models for the marginal costs of the financial instruments that are obtained after measuring the expected losses within the same LEC. For the marginal costs model, it is not necessary to measure the benefits because the minimum cost guarantees the highest benefit to the decision-maker. Nevertheless, a methodology was developed that made minor adjustments to the model by Mahul and Gurenko (2006) to be able to apply the available data for different countries, which, when parametrized, yield positive differences between costs and benefits using comparable metrics, with the benefit of implementing the risk mitigation measures considered in the first step.

3.2.1 Identification of mitigation measurements and financial instruments

The methodology assumes there are three levels of mitigation measures available including low (*lo*), medium (*m*) and high-risk incidence (*hi*). At the same time, it is assumed that the decision-maker has three additional financial instruments available including reserves (*r*), a contingent debt (*d*) and insurance coverage (*t*). Each combination between risk mitigation measures and financial instruments is referred to herein as a "*strategy*". To simplify the algorithm for the BCA, the study applies a single risk mitigation measure as proxy.

3.2.2 Identification of the set of available strategies

A disaster risk management *strategy* is defined as a set of risk mitigation measures and financial instruments that absorb[8], during a defined timeframe, a share of losses (L_B) caused by an eventual disaster.

$S = (s_1, s_2, \dots, s_i, \dots s_n)$ is defined as the discrete set of strategies with all possible combinations of, *f*, financial tools (*r, d* and *t*) and *m*, risk mitigation measures, with three impact levels (m_{lo}, m_m and m_{hi}).

The number of elements that determine the size of the set, *S*, is denoted as $\#S = \sum_k \binom{f+m}{k}$, which corresponds to the sum of all combinations of *f* and *m* in an array of size k, for all possible sizes of k.

In the example used in this chapter, which has four risk management instruments (three for *f* and one for *m*), the number of possible combinations is:

$$\#S = \binom{4}{1} + \binom{4}{2} + \binom{4}{3} + \binom{4}{4} = 4 + 6 + 4 + 1 = 15 \qquad \text{(3-27)}$$

---

[8] It is important to highlight that the concept of absorbing a loss, refers to the capacity than an action has to influence risk, which is in this case, the reduction of the net loss (to be absorbed by the decision-taker) as a result of implementing that specific measure.

Table 1 shows all the possible combinations.

Table 1. Considered DRR strategies

DRR Strategies
s_1 =Mitigation measure
s_2 =Insurance
s_3 =Reserves
s_4 =Contingent debt
s_5 =Mitigation and insurance
s_6 =Mitigation and contingent debt
s_7 =Mitigation and reserves
s_8 =Insurance and contingent debt
s_9 =Insurance and reserves
s_{10} =Contingent debt and reserves
s_{11} =Mitigation, contingent debt and insurance
s_{12} =Mitigation, contingent debt and reserves
s_{13} =Contingent debt, reserves and insurance
s_{14} =Mitigation, reserves and insurance
s_{15} =Mitigation, contingent debt, reserves and insurance

3.2.3 Identification of benefits and costs

3.2.3.1 Benefits

As mentioned before, in this study, benefits refers to differences between the expected present value of the gross loss (i.e. the loss value without a risk mitigation measure or coverage from a disaster financing instrument) and the net loss (i.e. the one a decision-maker is still responsible for after having purchased some type of coverage for a share of the gross loss), for each of the considered strategies.

In this study, a disaster risk management strategy is when the decision-maker has the following structure: a first segment covered by reserves, B_1, a variation in the LEC as a result of the implementation of a risk mitigation measure, B_2, a segment of retained losses by having engaged in a contingent debt, B_3, another segment covered by insurance, B_4 , and finally, another retained segment, B_5, where:

1. $B_i \cap B_j = \emptyset$
2. $\bigcup_{i=1}^{5} B_i = \mathrm{AAL}$

Figure 6 schematically shows the above-mentioned segmentation, considering that the layers and strategies on it are only indicative. The order and extent (i.e. the size of the range of losses) of each strategy in a real case will depend on local socioeconomic characteristics.

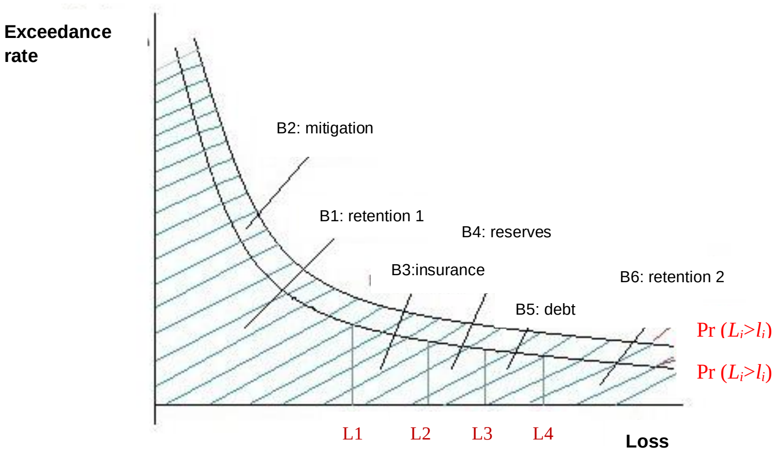


Figure 4. Schematic representation of the AAL segmentation.

It is worth noting that B_5, is not associated to any strategy in *S*. This share of losses can be understood as that one a government is forced to retain when it is not optimal or feasible to implement a risk mitigation measure or to use a financing instrument because of budgetary limitations.

Therefore, the benefit function $B(s_i) = B_i$ can be written as:

$$B(s_i) = B_i = Present\ expected\ value\ of\ the\ gross\ loss - Present\ expected\ value\ of\ the\ net\ loss = E\left[\sum_{i=1}^{\infty} l_{iB} * e^{-\partial t_i}\right] - E\left[\sum_{i=1}^{\infty} l_i{}^N * e^{-\partial t_i}\right] = E[L] - E[L^N] \qquad (3\text{-}28)$$

The mathematical expressions associated to all the strategies in Table 1 are shown next. For the time being, the limits of the disaster financing instruments follow the same order as in Figure 6. However, the following section explains how these limits can be modified to provide an efficient distribution of losses.

a. BENEFITS OF A RISK MITIGATION MEASURE, s_1

s₁ is estimated as:

$$B(s_1) = E\left[\sum_{i=1}^{\infty} l_{iB} * e^{-\partial t_i}\right] - E\left[\sum_{i=1}^{\infty} {l_i}^{N} * e^{-\partial t_i}\right] \tag{3-29}$$

where L^N corresponds to the expected losses once a risk mitigation measure has been implemented.

b. INSURANCE BENEFIT, s_2

s₂, can be estimated as:

$$B(s_2) = E\left[\sum_{i=1}^{\infty} l_{iB} * e^{-\partial t_i}\right] - E\left[\sum_{i=1}^{\infty} {l_i}^{N} * e^{-\partial t_i}\right] \tag{3-30}$$

where:

$$L^N = \begin{cases} L_B & si\ \ L_B < l_1 \\ l_1 & if\ \ \mathrm{l} \leq L_B \\ \leq\ l_2 & \\ L_B - (l_2 - \ l_1) & if \quad l_2 < L_B \end{cases} \tag{3-31}$$

c. RESERVE FUNDS BENEFIT, s_3

s₃ is estimated as:

$$B(s_3) = E\left[\sum_{i=1}^{\infty} l_{iB} * e^{-\partial t_i}\right] - E\left[\sum_{i=1}^{\infty} {l_i}^{N} * e^{-\partial t_i}\right] \tag{3-32}$$

where:

$$L^N = \begin{cases} L_B & si\ \ L_B < l_2 \\ l_2 & si\ \ l_2 \leq L_B \\ \leq\ l_3 & \\ L_B - (l_3 - \ l_2) & si \quad l_3 < L_B \end{cases}$$

(3-33)

d. CONTINGENT DEBT BENEFIT, s_4

s_4 is estimated as:

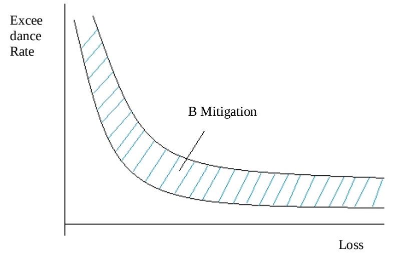
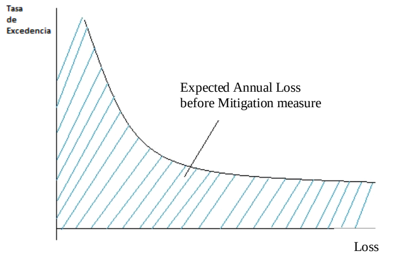
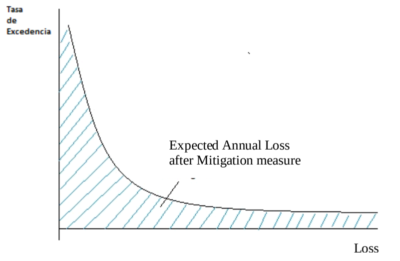
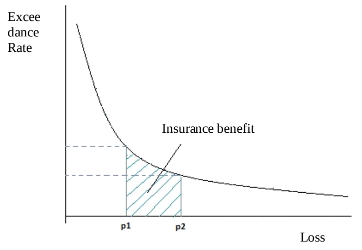
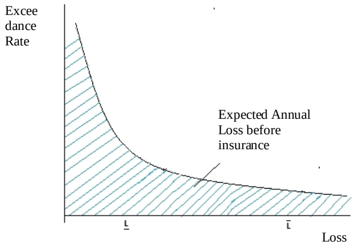
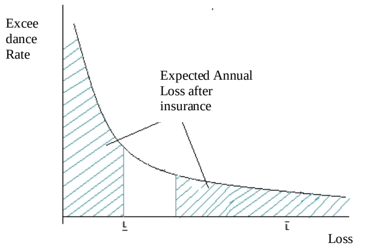
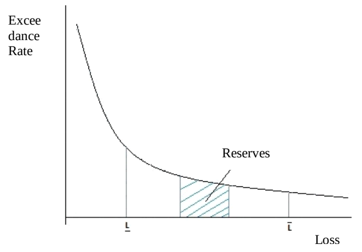
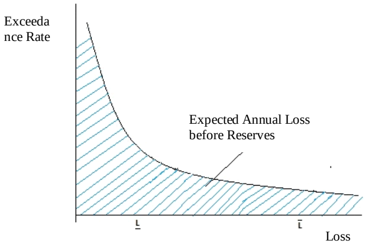
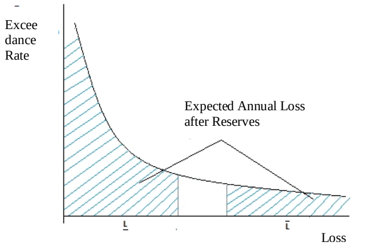
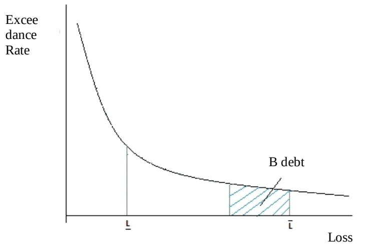
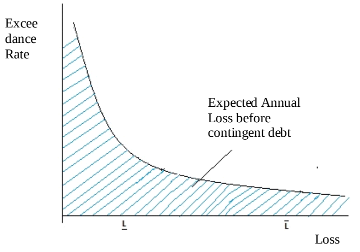
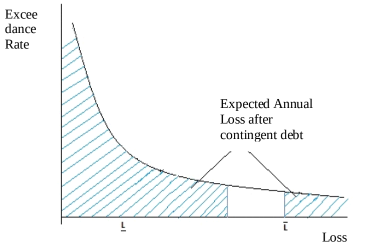
$$B(s_4) = E\left[\sum_{i=1}^{\infty} l_{iB} * e^{-\partial t_i}\right] - E\left[\sum_{i=1}^{\infty} l_i{}^N * e^{-\partial t_i}\right] \tag{3-34}$$

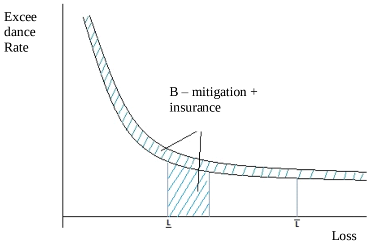
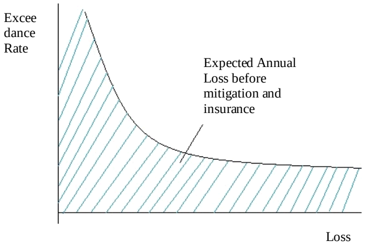
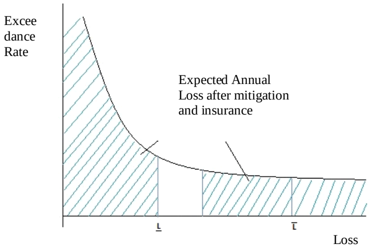
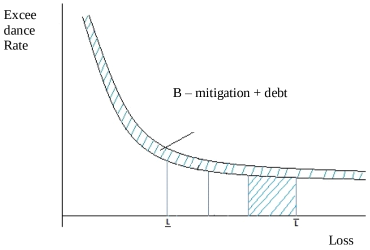
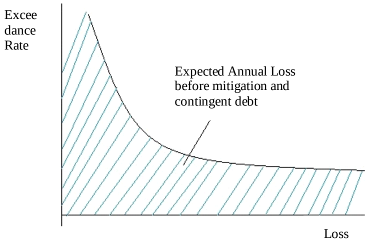
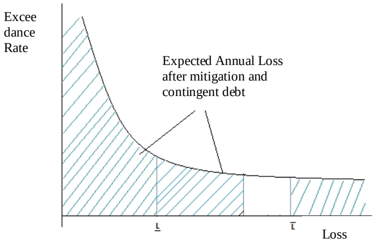
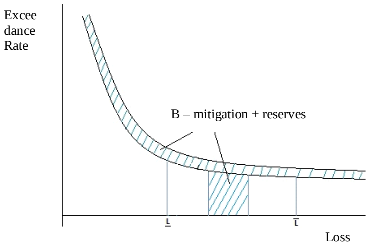
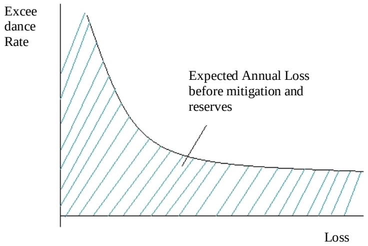
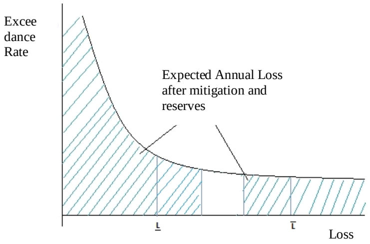
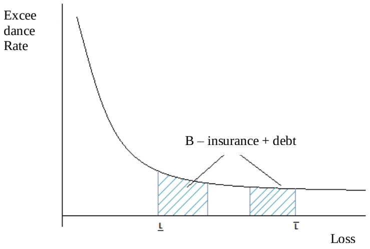
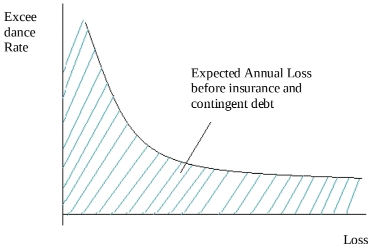
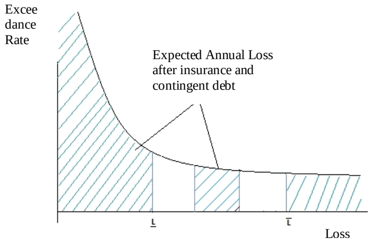
where:

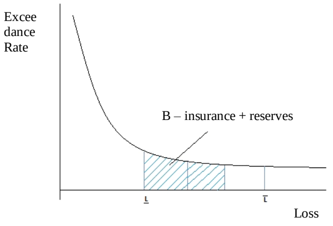
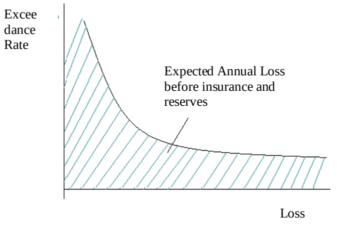
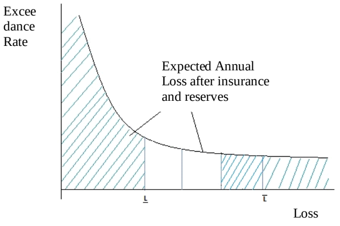
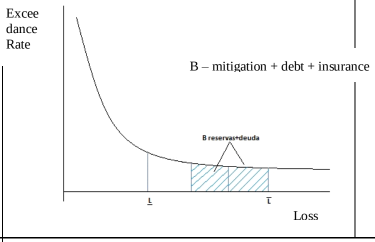
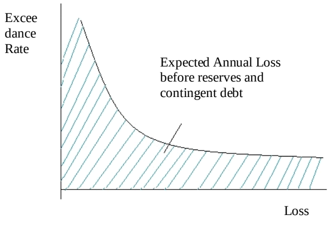
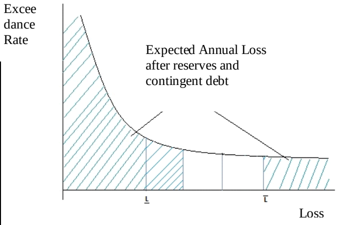
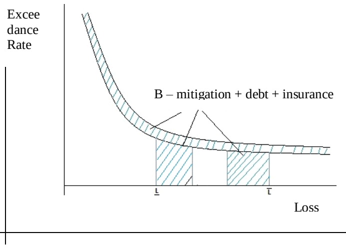
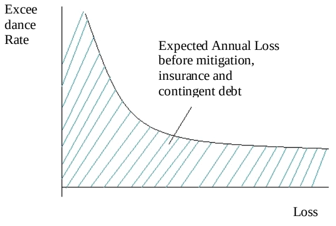
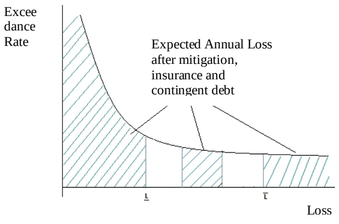
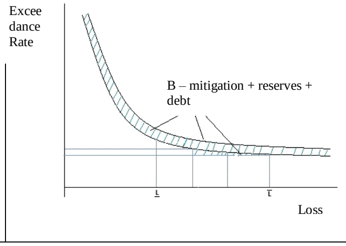
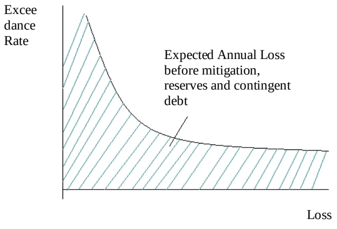
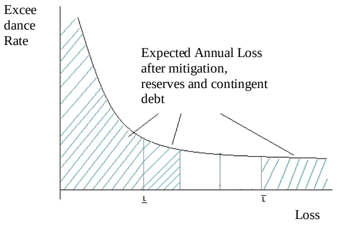
$$L^N = \begin{cases} L_B & if\ \ L_B < l_3 \\ l_3 & if\ \ l_3 \le L_B \ \le \ l_4 \\ L_B - (l_4 - \ l_3) & if \quad l_4 < L_B \end{cases} \tag{3-35}$$

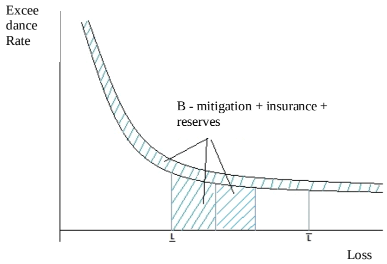
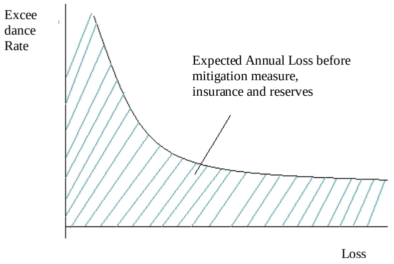
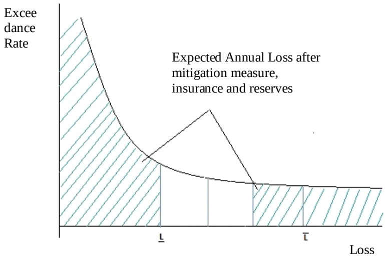
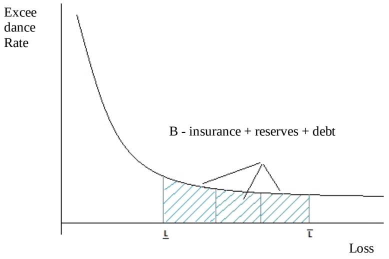
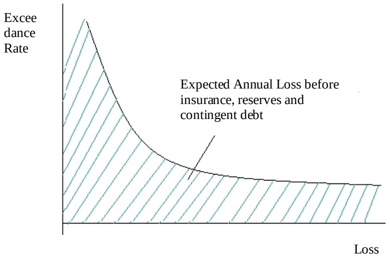
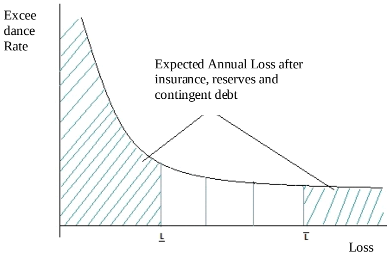
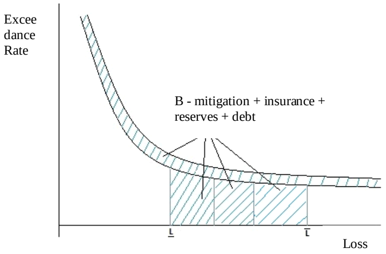
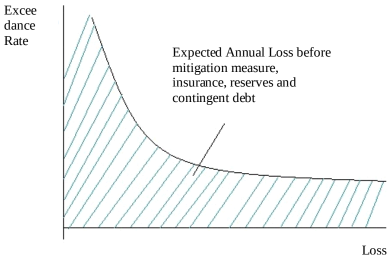
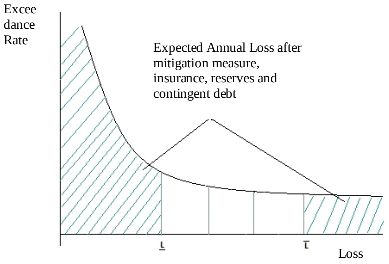
The overall benefits of the strategies that combine more than one instrument can be calculated by summing the individual benefits because they can be summed. Table 2 illustrates the ways in which the loss intervals associated to each of the strategies interact.

Table 2. Graphical representation of the interaction of the loss protection limits associated to the strategies

Combinations	$\binom{4}{1} =$				4
Strategies	Repartition of Z		Expected Annual Loss before Strategy		Expected Annual Loss after Strategy
1. Mitigation Measure (S1)		=		-	
2. Insurance (S2)		=		-	
3. Reserves (S3)		=		-	
4. Contingent debt (S4)		=		-	

Combinations	$\binom{4}{2}$ =				6
Strategies	Repartition of Z		Expected Annual Loss before Strategy		Expected Annual Loss after Strategy
5. Mitigation and Insurance (S5)		=		-	
6. Mitigation and Contingent Debt (S6)		=		-	
7. Mitigation and Reserves (S7)		=		-	
8. Insurance and Contingent Debt (S8)		=		-	

Combinations	$\binom{4}{2}$ =				6
Strategies	Repartition of Z		Expected Annual Loss before Strategy		Expected Annual Loss after Strategy
9. Insurance and Reserves		=		-	
10. Contingent Debt and Reserves (S10)		=		-	
Combinations	$\binom{4}{3}$ =				4
Strategies	Repartition of Z		Expected Annual Loss before Strategy		Expected Annual Loss after Strategy
11. Mitigation, Contingent Debt and Insurance		=		-	
12. Mitigation, Contingent Debt and Reserves		=		-	

Combinations	$\binom{4}{3}$ =				4
Strategies	Repartition of Z		Expected Annual Loss before Strategy		Expected Annual Loss after Strategy
13. Mitigation, Reserves and Insurance		=		-	
14. Contingent Debt, Reserves and Insurance		=		-	
Combinations	$\binom{4}{4}$ =				1
Strategies	Repartition of Z		Expected Annual Loss before Strategy		Expected Annual Loss after Strategy
15. Mitigation, Insurance, Reserves and Contingent Debt		=		-	

3.2.3.2 COSTS

The cost of acquiring any of the disaster financing instruments is associated to the "integration limits" (i.e. the range of losses) of each of them. These limits provide the range of the LEC to be covered by each instrument, in the event of a loss. On the other hand, it should be noted that both, the unitary costs of each instrument as well as its limits within the loss interval, will be modified as a function of a wide variety of economic and financial factors, together with the characteristics of the intensity and frequency of the hazardous events in the country under study.

From this perspective, the BCA in this methodology is used to find the optimal selection of measures and instruments, as a function of their costs and benefits, considering two steps[9]. The first step consists of defining the resource gap, which is to be understood as the range of losses between $[\underline{L}, \bar{L}]$ (where $\underline{L}$, in this study is equal to 0, and $\bar{L}$ is the upper limit of the *ex-ante* financing) as shown in Figure 7. This range describes the values of losses that the country, which acts as a decision-maker, is not able to cover with its own resources, but because *ex-ante* financing is a viable option, after accessing these instruments, would not require international assistance.

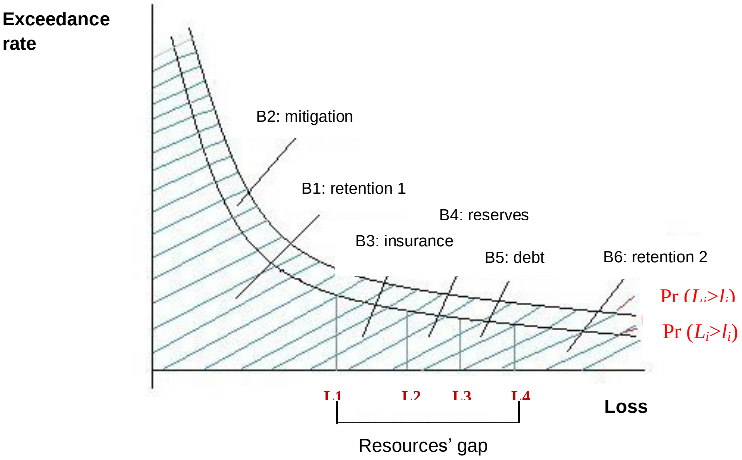


Figure 5. Definition of the resources' gap $[\underline{L}, \bar{L}]$

a. INSURANCE COST, s_2

According to Mahul and Gurenko (2006), the overall cost of an insurance premium can be broken down as: premium = expected loss + operation costs + capital costs. Considering an insurance instrument that provides coverage for losses in the range of [0, L], its expected

---

[9] Based on "*The Macro Financing of Natural Hazards in Developing Countries"* by Mahul and Gurenko (2006).

loss could be defined as $E[\min(\tilde{l}, L)]$ and therefore, the net premium of the expected loss could be assumed as:

$$P(L) = g(L) + d(L) \qquad (3\text{-}36)$$

where $P(L)$ is the net premium of the expected loss, $\tilde{l}$ represents the random loss, $g(L)$ represents the capital costs and $d(L)$ the operational costs.

Equation 3-36 indicates that the insurance cost is determined by its coverage limit [L]. $g(L)$ increases proportionally to increasing rates as the beginning of the coverage does the same, whereas $d(L)$ increases for decreasing rates as the beginning of the coverage increases. Because of this, the function of the net marginal cost of insurance for the expected loss, is U-shaped (see Figure 8).

Thus:

$$P'(L) = g'(L) + d'(L) \qquad (3\text{-}37)$$

b. RESERVE FUNDS COSTS, S_3

$$C(S_3) = S(L) = \frac{l_s - s}{1+r}L \qquad with\, l_s \geq s \qquad (3\text{-}38)$$

$$S'(L) = \frac{l_s - s}{1+r} \qquad with\, l_s \geq s \qquad (3\text{-}39)$$

where S is the net present value of the reserves, p_s the social discount rate, s the risk-free rate and r is the inflation rate of the country under study.

The social discount rate is the price used to assess the social cost-effectiveness of public investments. This model is different from the one used by Mahul and Gurenko (2006) on this aspect because they define the opportunity cost of a government as the growth rate of the GDP. Even if this assumption is reasonable for countries in which public investment accounts for much of the growth, it is not suitable for countries where the economic growth is driven by domestic consumption. Moreover, it is common practice in developing countries to assess public investment projects in the light of pre-established social discount rates. Except for this discrepancy, the results of this model and those of Mahul and Gurenko (2006) are consistent.

c. CONTIGENT DEBT COST, S_4

The cost of credit for a materialized loss, L, is defined as:

$$C(S_4) = h(L) = \left[l_f + \left(\frac{1+l_r}{1+r}\right)^m - 1\right] E\, min(\tilde{l}, L) + l_c\left[L - E \min(\tilde{l}, L)\right] \qquad (3\text{-}40)$$

where $h(L)$ represents the expected value of the contingent debt, l_f the loan acquisition fee, l_r the interest rate for the total borrowed amount, r the inflation rate for the country of study (where $r<l_r$), l_c the fixed rate charged for the unpaid loan amounts and m the expiration term.

The two components of this expression are the following:

$$h(L) = \begin{cases} \left[l_f + \left(\frac{1+l_r}{1+r}\right)^m - 1\right] E\, min(\tilde{l}, L), & interest\ paid\ on\ loan\ \tilde{l} \\ l_c\left[L - E \min(\tilde{l}, L)\right], & interest\ charged\ on\ unpaid\ amount \end{cases}$$

(3-41)

Equally:

$$h'(L) = \left[l_f + \left(\frac{1+l_r}{1+r}\right)^m - 1\right][v(l)] + l_c F_l(L) > 0 \qquad (3\text{-}42)$$

And,

$$h''(L) = -\left[l_f + \left(\frac{1+l_r}{1+r}\right)^m - 1 - l_c\right] f(L) < 0 \qquad (3\text{-}43)$$

where $f(L) = \left[\frac{d}{dl} F_l(l)\right] = \frac{d}{dl}\left[1 - \frac{v(l)}{N}\right]$ is the loss density function.

d. MINIMIZATION OF COSTS

Once the total and marginal costs of the financial instruments are defined, the estimation of the resource gap can be solved as follows:

$$Min_{[\underline{L}, \overline{L}]}\{L'(L), S'(L), h'(L)\} \qquad (3\text{-}44)$$

The solution to this problem allows to identify the limits that efficiently assign the financial instruments over the resource gap. This delimitation is graphically shown in Figure 8, where the purple line shows the behavior of the net marginal premium of the expected loss. The blue line depicts the marginal value of the contingent debt and the brown line shows the marginal value of the reserves. Besides this, the parts shown in red indicate the optimal combination of financial instruments to cover the resource's gap, and the colored horizontal bars at the bottom of the graph indicate the range for which each of the financial instruments is found to be optimal (these colors are to be linked to the colors used in the definition of the instruments in the same figure).

Another relevant aspect and assumption to highlight, which is in line with Mahul and Gurenko (2006), is that the decision to purchase coverage from financial instruments occurs at the beginning. This means that the acquisition of insurance and/or contingent credit, or the constitution of annual reserves (and the horizon on which those will be replenished), will occur at the starting point of the timeframe subject to optimization. The model does not consider any societal costs caused by the extinction of the reserve and suggests a dynamic model. Given that the capacity to generate reserves funds in Latin American and Caribbean countries is very limited, this study does not consider this refinement to the model as adequate since the cost of using the reserves becomes more expensive.

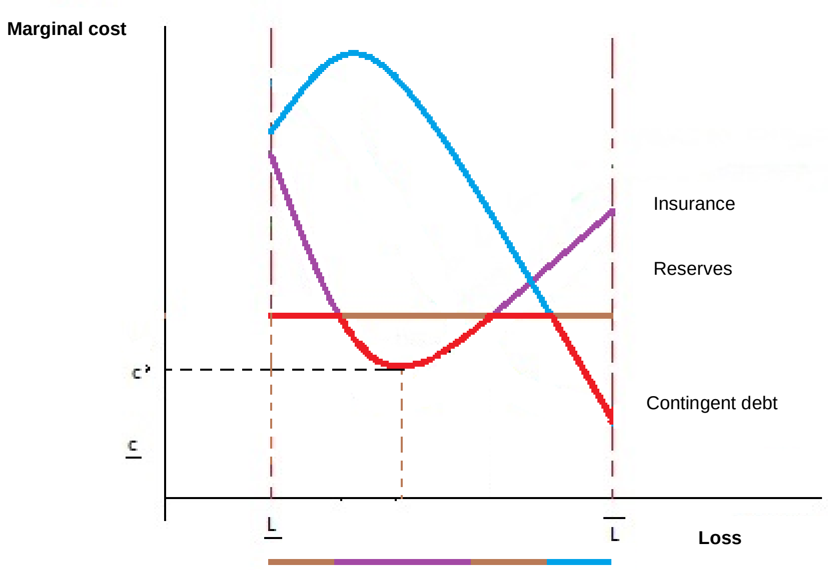


Figure 6. Graphical solution to the combination of financial instruments.
Source: Mahul and Gurenko (2006)

e. RISK MITIGATION MEASURES COSTS

The costs of risk mitigation measures are the result of civil and structural engineering analyses (by building typology) and other characteristics of the location, where the risk mitigation measure is to be implemented. In the BCA, these costs are assumed to be constant.

The cost of the risk mitigation measure is defined as:

$$C(s_1) = C \qquad (3\text{-}45)$$

Finally, the costs of the remaining strategies are shown next.

RISK MITIGATION AND INSURANCE COST, $\boldsymbol{s_5}$

$$C(s_5) = C(s_1) + C(s_2) \tag{3-46}$$

RISK MITIGATION AND CONTINGENT DEBT COST, $\boldsymbol{s_6}$

$$C(s_6) = C(s_1) + C(S_4) \tag{3-47}$$

RISK MITIGATION AND RESERVES COST, $\boldsymbol{s_7}$

$$C(s_7) = C(s_1) + C(S_3) \tag{3-48}$$

INSURANCE AND CONTINGENT DEBT COST, $\boldsymbol{s_8}$

$$C(s_8) = C(s_2) + C(S_4) \tag{3-49}$$

INSURANCE AND RESERVES COST, $\boldsymbol{s_9}$

$$C(s_9) = C(s_2) + C(S_3) \tag{3-50}$$

CONTINGENT DEBT AND RESERVES COST, $\boldsymbol{s_{10}}$

$$C(s_{10}) = C(s_4) + C(S_3) \tag{3-51}$$

RISK MITIGATION, CONTINGENT DEBT AND INSURANCE COST, $\boldsymbol{s_{11}}$

$$C(s_{11}) = C(s_4) + C(S_2) \tag{3-52}$$

RISK MITIGATION, CONTINGENT DEBT AND RESERVES COST, $\boldsymbol{s_{12}}$

$$C(s_{12}) = C(s_1) + C(S_4) + C(s_3) \tag{3-53}$$

CONTINGENT DEBT, RESERVES AND INSURANCE COST, $\boldsymbol{s_{13}}$

$$C(s_{13}) = C(s_4) + C(S_3) + C(s_2) \tag{3-54}$$

RISK MITIGATION, RESERVES AND INSURANCE COST, $\boldsymbol{s_{14}}$

$$C(s_{14}) = C(s_1) + C(S_3) + C(s_2) \tag{3-55}$$

RISK MITIGATION, CONTINGENT DEBT, RESERVES AND INSURANCE COST, $\boldsymbol{s_{15}}$

$$C(s_{15}) = C(s_1) + C(S_4) + C(s_3) + C(s_2) \tag{3-56}$$

3.2.4 Cost leverage per unitary benefit

The BCA can also be analyzed as the cost leverage, where each of its monetary units is leveraged and translated into benefit units. In this sense, the B/C ratio is the leverage rate.

Further on in this document, all references made to benefits and costs will be associated to the concept of cost leverage.

3.2.5 Cost quantification over time

Usually the costs of all strategies are estimated at *t*=0 by calculating their present value. On the one hand, the costs of the financial instruments must be discounted over time and, on the other hand, estimations for the risk mitigation measures, using the present value, are to be made for *t*=0.

Benefits are obtained, in an annual basis, for the total lifetime of the risk mitigation measures, as schematically shown in Figure 9.

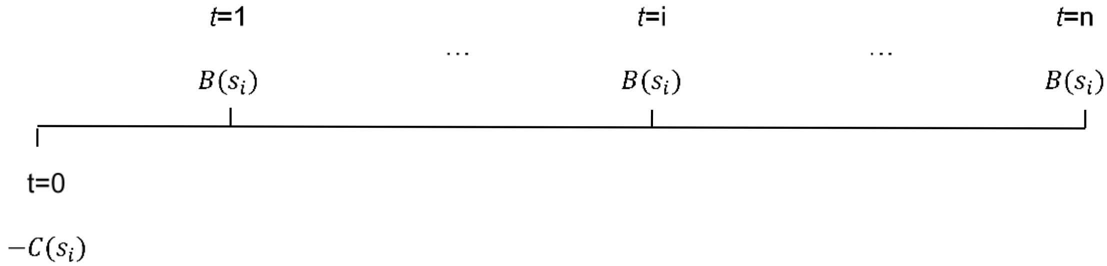


Figure 9. Schematic representation for the cost quantification over the time

In analytical terms, the present value of the benefits (*PVB*) can be estimated as:

$$PVB = \sum_{t=1}^{n} B(s_i) * e^{-\partial t} \qquad (3\text{-}57)$$

The timeframe for the analysis is the total number of years in which benefits associated to the risk mitigation measures will be evaluated. The choice of the length of the timeframe has to do with the BCA, since if affects the selection criteria, $Max\ \frac{B}{C}$, of the optimal strategy.

3.2.6 Comparison of the flows for benefits and costs of the strategies

The comparison of flows for the benefits and costs during the timeframe defined in this study is reflected in the B/C ratio. This comparison must be made by estimating the present value and using a discount rate to consider the value of money over time.

a. Discount rate associated to benefits and costs

The benefits from any strategy are to be measured using the same monetary units. Therefore, the discount rate to be used needs to be the social discount rate, which reflects the efforts that a country must make for each monetary unit required to finance a new investment project. It is worth mentioning that, if the capital market is imperfect, this discount rate may not coincide with the financial rate of return.

There are several approaches related to the interpretation and choice of the value for the social discount rate. For the purposes of this methodology, the social discount rate will be set by the decision-maker and therefore, it is an input of the economic model.

b. Present value of the costs

After all, the present value of the costs (*PVC*) is obtained after discounting cash flows over time. For instance, if Z_t represents the costs associated to a strategy during period t, ∂ is the discount rate of the strategy, and a timeframe of N years is used, its present value will be:

$$PVC = \sum_{t=0}^{n-1} Z_t * e^{-\partial t} \tag{3-58}$$

The B/C ratio can then be calculated as:

$$\frac{B}{C} = \frac{PVB}{PVC} \tag{3-59}$$

Based on the previous explanation, the B/C ratio is calculated for all strategies. This B/C ratio allows solving the maximization problem of the following step of the BCA.

c. Selection of the optimal strategy

Lastly, by using the information included in Table 3, it is possible to make comparisons between the different strategies so that the selection of the optimal one is made.

Table 3. B/C tables for the considered strategies

STRATEGY	BENEFIT =Present value of the equation #	COST = equation #	B/C
s_1= Mitigation measure	$B(s_1) = Present\ value\ of\ (1)$	$C(s_1) = (8)$	$\frac{B(s_1)}{C(s_1)}$
s_2= Insurance	$B(s_2) = Present\ value\ of\ (2)$	$C(s_2) = (5)$	$\frac{B(s_2)}{C(s_2)}$
s_3= Reserves	$B(s_3) = Present\ value\ of (3)$	$C(s_3) = (6)$	$\frac{B(s_3)}{C(s_3)}$
s_4= Contingent debt	$B(s_4) = Present\ value\ of\ (4)$	$C(s_4) = (7)$	$\frac{B(s_4)}{C(s_4)}$
s_5= Mitigation and insurance	$(s_5) = Present\ value\ of\ (1) + (2)$	$C(s_5) = (9)$	$\frac{B(s_5)}{C(s_5)}$
s_6= Mitigation and contingent debt	$B(s_6) = Present\ value\ of\ (1) + (4)$	$C(s_6) = (10)$	$\frac{B(s_6)}{C(s_6)}$
s_7= Mitigation and reserves	$B(s_7) = Present\ value\ of\ (1) + (3)$	$C(s_7) = (11)$	$\frac{B(s_7)}{C(s_7)}$
s_8= Insurance and contingent debt	$(s_8) = Present\ value\ of\ (2) + (4)$	$C(s_8) = (12)$	$\frac{B(s_8)}{C(s_8)}$
s_9= Insurance and reserves	$(s_9) = Present\ value\ of\ (2) + (3)$	$C(s_9) = (13)$	$\frac{B(s_9)}{C(s_9)}$
s_{10}= Contingent debt and reserves	$(s_{10}) = Present\ value\ of\ (4) + (3)$	$C(s_{10}) = (14)$	$\frac{B(s_{10})}{C(s_{10})}$
s_{11}= Mitigation, contingent debt and reserves	$B(s_{11}) = Present\ value\ of\ (1) + (4) + (2)$	$C(s_{11}) = (15)$	$\frac{B(s_{11})}{C(s_{11})}$
s_{12}= Mitigation, contingent debt and reserves	$B(s_{12}) = Present\ value\ of\ (1) + (4) + (3)$	$C(s_{12}) = (16)$	$\frac{B(s_{12})}{C(s_{12})}$
s_{13}= Contingent debt, reserves and insurance	$B(s_{13}) = Present\ value\ of\ (4) + (3) + (2)$	$C(s_{13}) = (17)$	$\frac{B(s_{13})}{C(s_{13})}$
s_{14}= Mitigation, reserves and insurance	$B(s_{14}) = Present\ value\ of\ (1) + (3) + (2)$	$C(s_{14}) = (18)$	$\frac{B(s_{14})}{C(s_{14})}$
s_{15}= Mitigation, insurance, reserves and contingent debt	$B(s_{15}) = Present\ value\ of\ (1) + (2) + (3) + (4)$	$C(s_{15}) = (19)$	$\frac{B(s_{15})}{C(s_{15})}$

3.3 MONTE CARLO LOSS SIMULATION METHOD

3.3.1 Context for the simulation

This section introduces the empirical approach to estimate the benefits of a strategy using simulations based on the LEC for the country under analysis. A numerical simulation approach, specifically the Monte Carlo loss simulation is chosen for quantifying the benefits of the BCA in this study. This section is organized as follows: first, an introduction to the origins and reasons to use a simulation approach is presented, followed by the description of the inverse transform method, which is commonly used to perform Monte Carlo simulations. Finally, an explanation is provided about using these methods to solve integrals.

3.3.2 Introduction to the simulation

A simulation is defined as the imitation of a process in the real world over time. Simulation methods are commonly used to solve problems in fields where no analytical solutions exist for the cases of interest. The development of these methods began with the study of patterns that did not have any defined behavior, but for which there were some basic data about its occurrence. The importance of these available data is that with them, occurrence probabilities for separate events can be estimated, which can predict results for a complete sequence of events.

The robustness of a simulation lies in its ability to generate random numbers between zero and one[10], which can be related, in some way, to possible values associated to the process which is being replicated. These numbers are a succession of values that, although are being generated in a deterministic manner, have the appearance of being random, uniform and independent variables, always with values between zero and one.

3.3.3 Algorithm for the inverse transform method

The inverse transform method makes use of the cumulative distribution $F_X(x) = \Pr(X \leq x)$ of the distribution to be simulated. This function, $F_X(x)$, has the following characteristics:

1. $0 \leq F_X(x) \leq 1$
2. It is increasing. (i.e. if *a*<*b* then, $F_X(a) \leq F_X(b)$ for any random variable *X*)

Because $F_X(x)$, like any probability, has always values between zero and one, a random variable, *U*, can be generated within that interval, having the following form:

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[10] Because any probability value must be between these two values

$U \sim uniform(0,1)$. Then, the value of the random variable *x* for which its cumulative distribution, $F_X(x)$, is equal to *U* is attempted to be determined.

As mentioned before, when data about the occurrence of uncertain events are available, it is possible to associate an occurrence probability to random variable *X* in the following way: $U = F(X)$ or, what is equivalent, $X = F^{-1}(U)$. The conceptual development for this is shown next:

$$F_X(x) = \Pr(X \leq x) = \Pr\,[F^{-1}(U) \leq x] \tag{3-60}$$

Since function *F*(*X*) is increasing for any random variable, the expression (3-60) can be re-written as:

$$F_X(x) = \Pr\{F[F^{-1}(U)] \leq F(x)\} = \Pr[U \leq F(x)] = F_U[F(x)] \tag{3-61}$$

The family of uniform probability distributions, for any parameters *a* and *b*, has the following characteristics:

$$a \leq u \leq b$$

$$\Pr(U = u) = f_U(u) = \frac{1}{b-a} \qquad for\ a \leq u \leq b \tag{3-62}$$

$$\Pr(U \leq u) = F_U(u) = \frac{u-a}{b-a} \qquad for\ a \leq u \leq b \tag{3-63}$$

In our case *a*=0 and *b*=1, meaning that $F_U[F(x)] = \frac{F(x)-a}{b-a} = F(x) = u$.

Therefore, from a continuous function *F* that relates values of $F_X(x) = u$ (which are always between zero and one) with their respective values of *x*, it is possible to generate as many numbers as needed.

A characteristic of this method, which is one of its main advantages, is that it is not mandatory to define the general functional form of $F_x(x)$ to carry out the simulations. This means that there is no need to perform goodness of fit tests to determine which of the distributions in the statistical literature[11] adjusts best to the LEC, and with the data, calibrate the parameters that characterize them to be able to perform the simulation.

---

[11] Gamma, Beta, Exponential, Weibull, Uniform, Pareto and Normal, among others

This attribute prevents us of using more complex numerical processes. However, it does not exempt us to find a way to relate the random numbers, between 0 and 1, with the variable of analysis. This relationship can be established through the LEC and is explained in the following section.

3.4 EMPIRICAL PROCEDURE TO ESTIMATE THE BENEFITS OF THE STRATEGIES

3.4.1 Simulation of the gross losses

The processes described in the previous sections can be used to carry out simulations of losses based on the LEC. The LEC relates the amount of a loss with its annual exceedance rate, providing a precise notion of how to relate a random number, between 0 and 1, to a loss value l_i. The LEC does not allow having a form for the cumulative distribution function, such as $F_X(x) = \Pr(X \leq x)$, but a series of non-exceedance probability points.

When exceedance rates $v(l)$ are available, their associated probabilities can be obtained after dividing them by the number of recorded events. At the same time, non-exceedance probabilities can be estimated as:

$$Non - exceedance\ probability = 1 - Exceedance\ probability \qquad (3\text{-}64)$$

The random numbers generated will come from a uniform density function with values between 0 and 1, guaranteeing their congruence with a feasible probability value. Having these random numbers associated to a uniform distribution means that the probability of a realization, yielding a number between 0 and 1, is the same for any value within the interval, ensuring that there is no occurrence bias for the values generated by the simulation.

In section 3.3.3, the cumulative distribution was defined as $F_X(x) = \Pr(X \leq x)$, where X is a random variable. In this study, and as explained in section 3.1.1, the random variable of interest corresponds to the loss (L_i). Therefore, its non-exceedance probability distribution function is $F_{L_i}(l_i) = \Pr(L_i \leq l_i)$.

Additionally, in section 3.3.3, function F^{-1} described the relationship between the variable of study X and random variable U with a uniform distribution between 0 and 1. In this study, the function F^{-1} seeks to relate each of the "*m*" generated random numbers with a loss value. This process is graphically explained in Figure 10.

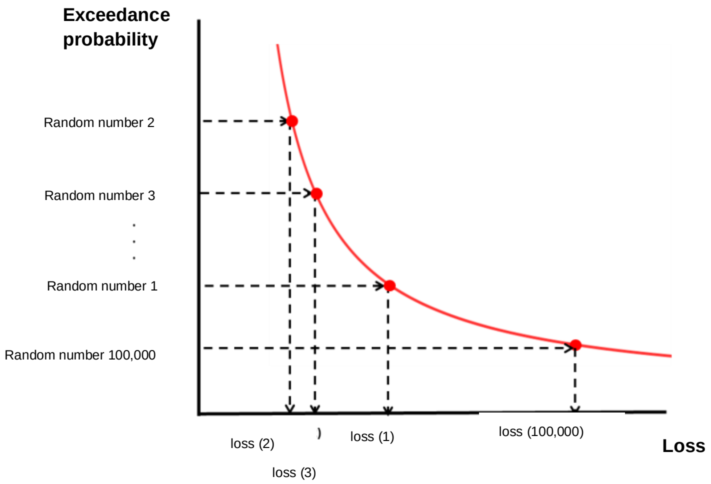


Figure 10. Correspondence between a simulation of exceedance probabilities and gross losses.

The objective of simulating exceedance probabilities and their associated losses is to generate loss levels compatible with the reality described by the LEC of the country under study. As shown in Figure 10, the amount of the simulated losses does not follow a particular order and therefore, very small or large losses can occur from one moment to another, as in reality.

The curve data is generated from a risk assessment and the corresponding probabilities are calculated using the formulas described at the beginning of this section. With that, it is possible to organize the Table 4.as follows.

Table 4. Description of the application of the simulation

Loss (L_i)	**Exceedance rate v** (l_i)	**Exceedance probability**	**Non-exceedance probability**
L_1	v (l_1)	$\frac{\mathrm{v}(l_1)}{N}$	$F_{L_i}(l_1) = 1 - \frac{\mathrm{v}(l_1)}{N}$
L_2	v (l_2)	$\frac{\mathrm{v}(l_2)}{N}$	$F_{L_i}(l_2) = 1 - \frac{\mathrm{v}(l_2)}{N}$
L_3	v (l_3)	$\frac{\mathrm{v}(l_3)}{N}$	$F_{L_i}(l_3) = 1 - \frac{\mathrm{v}(l_3)}{N}$
L_4	v (l_4)	$\frac{\mathrm{v}(l_4)}{N}$	$F_{L_i}(l_4) = 1 - \frac{\mathrm{v}(l_4)}{N}$
L_5	v (l_5)	$\frac{\mathrm{v}(l_5)}{N}$	$F_{L_i}(l_5) = 1 - \frac{\mathrm{v}(l_5)}{N}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
L_J	v (l_J)	$\frac{\mathrm{v}(l_J)}{N}$	$F_{L_j}(l_J) = 1 - \frac{\mathrm{v}(l_J)}{N}$

It is important to highlight that the number of loss points provided by the risk assessment is different from the number of randomly generated values (J $\neq M$). Therefore, based on the obtained random number, u_i, its corresponding L_i value can be estimated in the following way:

1. u_i is placed between two non-exceedance probability values $F_{L_i}(l_\text{i})$, denoted as $F_{L_{i-1}}(l_{\text{i}-1})$ and $F_{L_{i+1}}(l_{\text{i}+1})$ that comply with the following condition: $F_{L_{i-1}}(l_{\text{i}-1}) \leq u_i \leq F_{L_{i+1}}(l_{\text{i}+1})$.
2. $F_{L_{i-1}}(l_{\text{i}-1})$ and $F_{L_{i+1}}(l_{\text{i}+1})_{\text{i}-1}$ are related with their respective loss values, $L_{\text{i}-1}$ and $L_{\text{i}+1}$.
3. The slope between these points is estimated using the following formula: $m = \frac{\Delta L}{\Delta F} = \frac{L_{\text{i}+1} - L_{\text{i}-1}}{F_{L_{i+1}}(l_{\text{i}+1}) - F_{L_{i-1}}(l_{\text{i}-1})}$
4. Ordinate, to origin *b*, is defined as: $b = L_{i+1} - [m^* F_{L_{i+1}}(l_{\text{i}+1})]$
5. Loss, $L_i(U_i)$, associated to random number u_i is calculated as: $L_i(U_i) = m * U_i + b$
6. The process is repeated for each of the "*m*" simulations that were performed

Based on the law of large numbers, the larger the number of simulated losses, the higher the accuracy of the results with respect to the LEC that was used as a reference.

3.4.2 Simulation of occurrence time between losses

Once several loss simulations have been performed, the next step is to simulate their occurrence times. At this stage, it is assumed that occurrence times follow an exponential distribution. This allows for the modelling of the time distribution until the occurrence of a specific event, which in this case is the occurrence of a disaster that causes one of the simulated losses. The definition of an exponential distribution is the following:

$X \sim Exp\ (\beta)$ if:

$$f_X(x) = \frac{1}{\beta} e^{-\frac{x}{\beta}} I_{(0,\infty)}(x) \qquad \beta > 0 \tag{3-65}$$

By having a parametrization for $f_X(x)$, its cumulative density function $F_X(x)$ can be expressed as:

$$F_X(x) = 1 - e^{-\frac{x}{\beta}} \tag{3-66}$$

When using the inverse transform method, random numbers associated to a uniform distribution are always generated with values between 0 and 1, so that they correspond to probability values. When simulating numbers from known distribution groups, such as the exponential one, what is associated to these random numbers is function $F_X(x)$.

$$e^{-\frac{x}{\beta}} = 1 - F_X(x) = \frac{1}{e^{\frac{x}{\beta}}} \quad (3\text{-}67)$$

$$so \quad e^{\frac{x}{\beta}} = \frac{1}{1-F_X(x)} = [1 - F_X(x)]^{-1} \quad (3\text{-}68)$$

$$\frac{x}{\beta} = -\ln[1 - F_X(x)] \quad \therefore x = -\beta * ln[1 - F_X(x)] \quad (3\text{-}69)$$

Because of the properties of the cumulative density functions:

$$0 \leq F_X(x) \leq 1 \quad (3\text{-}70)$$

$$-1 \leq -F_X(x) \leq 0 \quad (3\text{-}71)$$

$$0 \leq 1 - F_X(x) \leq 1 \quad (3\text{-}72)$$

And therefore, simulating a random number between 0 and 1 serves to replicate not only the values of $1 - F_X(x)$, but also those of $F_X(x)$.

Once the occurrence times between each loss are simulated, a counting of the accumulated elapsed time for each simulated loss is made. This elapsed time can be defined as the cumulative sum of the occurrence times between each loss. Table 5 shows an example.

Table 5. Example of the occurrence time simulation

Occurrence times between losses (year)	Elapsed occurrence times (year)	Simulated loss (US$ million)
0.68567705	0.68567705	3,636
0.64184846	1.32752552	164
3.73943762	5.06696314	129
1.96310746	7.0300706	1,176
3.93520632	10.9652769	1,053

Table 5 provides an example of the first simulated loss equaled US$3,636 million and, according to the simulation over time, occurred in year 0.68 (i.e. at the eighth month). The second loss, equaled US$164 million and occurred in year 1.32 (elapsed occurrence time), which indicates a period equal to 0.64 years between the first and the second losses (inter-event occurrence time). The realizations continue successively until reaching the final simulated loss, in this example equal to US$1,053 million, which occurred in year 10.96. This process is to be repeated several times (ideally more than 100,000 times) to have all data for a complete simulation.

The purpose of this loss simulation over time is to have a wide range for analysis that allows to identify the effects of the strategies on each simulated loss. The approach for calculating the benefits can be considered robust and accurate since the use of a financial instrument is evaluated for each simulated loss over a given timeframe.

3.4.3 Obtaining the net loss of a financial instrument

The net loss is that one resulting after having engaged in a strategy. This loss will always be less than, or equal to, the gross loss (i.e. the one obtained after choosing a strategy), depending on loss levels. For example, if the selected strategy only includes insurance coverage for the range of catastrophic losses between US $100 and 150 million, the net losses would be the following:

$$Net\ loss = \begin{cases} L_N & if\ L_N < 100 \\ 100 & if\ 100 \leq L_N \leq 150 \\ L_N - (150 - 100) & if\ 150 < L_N \end{cases} \qquad (3\text{-}73)$$

The definition of what is a net loss is made from a government perspective, which means that the net loss is that one to be absorbed by the one responsible for the losses after acquiring a strategy and without considering its acquisition cost. Using the values of the hypothetical strategy mentioned before, and the simulation values of Table 5, an additional column is shown in Table 6 indicating the net losses for each simulation.

Table 6. Example of gross and net loss for a given strategy

Occurrence times between losses (year)	Elapsed occurrence times (year)	Simulated gross loss (US$ million)	Net loss (US$ million)
0.68567705	0.68567705	3,636	3,586
0.64184846	1.32752552	164	114
3.73943762	5.06696314	129	100
1.96310746	7.0300706	1,176	1,126
3.93520632	10.9652769	1,053	1,003

3.4.4 Present value of the gross and net losses

To estimate the benefits of disaster financing instruments, it is necessary to obtain the present value of each simulated loss. For this reason, a discount rate must be defined for estimating a discount factor. The value for the discount rate, ∂, was discussed in previous sections and the discount factor for each accumulated occurrence time is calculated as:

$$e^{-\partial * \text{Accumulated occurrence time}} \tag{3-74}$$

The present value of each loss is obtained after multiplying the discount factor by the simulated gross loss. Continuing with the previous loss simulation example, and using a discount rate of 4.5%, Table 7 shows the net present value of the gross and net losses for each simulation.

Table 7. Present value of gross and net losses

Elapsed occurrence time (year)	Simulated gross loss (US$ million)	Net loss (US$ million)	Discount factor	Present value of gross loss flows (US$ million)	Present value of net loss flows (US$ million)
0.68567705	3636	3586	0.9696	3,525.52	3,477.04
1.32752552	164	114	0.9420	154.49	107.39
5.06696314	129	100	0.7961	102.7	79.61
7.0300706	1176	1126	0.7288	857.07	820.63
10.9652769	1053	1003	0.6105	642.88	612.36
TOTAL				**5,282.66**	**5,097.03**

3.4.5 Net present value of the losses and the benefit of an instrument

The net present value of the losses is the sum of the present value of net and gross loss flows. Using the example of Table 7 this would be:

- Net present value of gross losses = 5,282.66 (US$ million)
- Net present value of net losses = 5,097.03 (US$ million)

These figures correspond to the present value of all simulated losses over a period of 10.96 years. This example uses a short timeframe only. For the practical application of the methodology, it would be necessary to simulate many more events (e.g. *N*=100,000), which yield an infinite timeframe.

The benefit of a financial instrument can be estimated as the difference between the present net values of the gross and net losses.

$$Benefit = Present\ value_{Gross} - Present\ value_{Net} \tag{3-75}$$

In this example, the benefit would be equal to US$185.63 million.

3.4.6 Net loss of a strategy and its benefit

According to the previous sections, the BCA based its study on the generation of strategies, which are defined as the set of all possible combinations of risk mitigation measures, *m*, and financial instruments, *f: r, d* and *t.*

To better illustrate the definition of net loss in a strategy that includes more than one financial instrument, let's consider a case in which there are three financial instruments. Each one provides coverage for intervals defined by two loss levels, as a result of minimizing the marginal costs (see previous section).

If the loss intervals are assigned in the following way:

$$Insurance: \quad [l, l_2]$$

$$Contingent\ debt: \quad [l_2, l_3]$$

$$Reserves: \quad [l_4, l_5]$$

$$where: \ [l_1, l_2] \cup [l_2, l_3] \cup [l_4, l_5] = [\underline{L}, \overline{L}]$$

the net loss for each instrument would be:

$$Net\ loss = \begin{cases} L_B & if\ \ L_B < l_k \\ l_k & if\ \ l_k \leq L_B \leq l_{k+1} \\ L_B - (l_{k+1} - l_k) & if\ \ l_{k+1} < L_B \end{cases} \tag{3-76}$$

where L_B corresponds to the gross loss and $k \in \{1,2,3,4\}$.

Obtaining the benefit for each instrument is done in the same way as previously presented in this section, whereas the benefit of the strategy is the result of the sum of the individual benefits of each of the financial instruments that are part of it.

The benefit that results after several simulations of *N,* is simply one of many from a set of *N* simulations. Therefore, as required by the law of large numbers, it is necessary to repeat the process illustrated in appendix B a considerable number of times (say *“n”)* so that the average value of the estimated benefits approximates to the real one. In analytical terms this can be written as:

$$\frac{\sum_i^n Benefit\ of\ S\ strategy\ \text{of simulation}\ i}{n} \approx Real\ benefit\ of\ strategy\ S \tag{3-77}$$

4 RISK MITIGATION MEASURES

The objective of this chapter is to explain how the previously described model modifies the LEC after implementing a risk mitigation measure. The first step is to make use of the total probability theorem to obtain the LEC associated in the initial state (i.e. without a risk mitigation measure). After this, the effect of the risk mitigation measure is considered - in a simplified way- by a modification of the vulnerability functions, which in turn results in a new LEC. By following this procedure, new probabilistic risk assessment results are obtained for the modified scenario (i.e. that one that includes a risk mitigation measure).

This study includes a proposal of a parametric model to estimate loss exceedance rates that consider risk mitigation measures. This chapter is focused on the review of the main data sources and published studies that allow identifying different risk mitigation measures related to structural engineering, which are representative for the type of economies that are of interest in this study.

In the literature reviewed, a risk mitigation measure is understood as the implementation of a work and/or action which seeks to reduce the adverse impacts of a disaster before its occurrence. Risk mitigation strategies have relevance in the international disaster risk management community and should be efficiently implemented. However, in the context of limited financial resources of the countries in Latin American and Caribbean (LAC) region, the only viable option is to reduce up to some level the potential losses.

4.1 CONCEPTUAL APPROACH TO RISK MITIGATION

There are different risk mitigation measures that can be implemented in public infrastructure, which usually depend on other variables such as: its current damage, resistance system and structural characteristics of each construction.

Risk mitigation measures found in the reviewed literature consider the following parameters:

- Structural system
- Basic description of the asset (e.g., main use, number of stories)
- Year of Construction
- Types of risk mitigation measures proposed
- Cost of the risk mitigation measures to be implemented
- Expected benefits and other additional information.
- Economic appraisal of the asset (usually in terms of the replacement cost)

Figure 11 shows a general scheme of the steps to identify and select the most appropriate risk mitigation measure for a specific hazard, which are explained with more detail next.

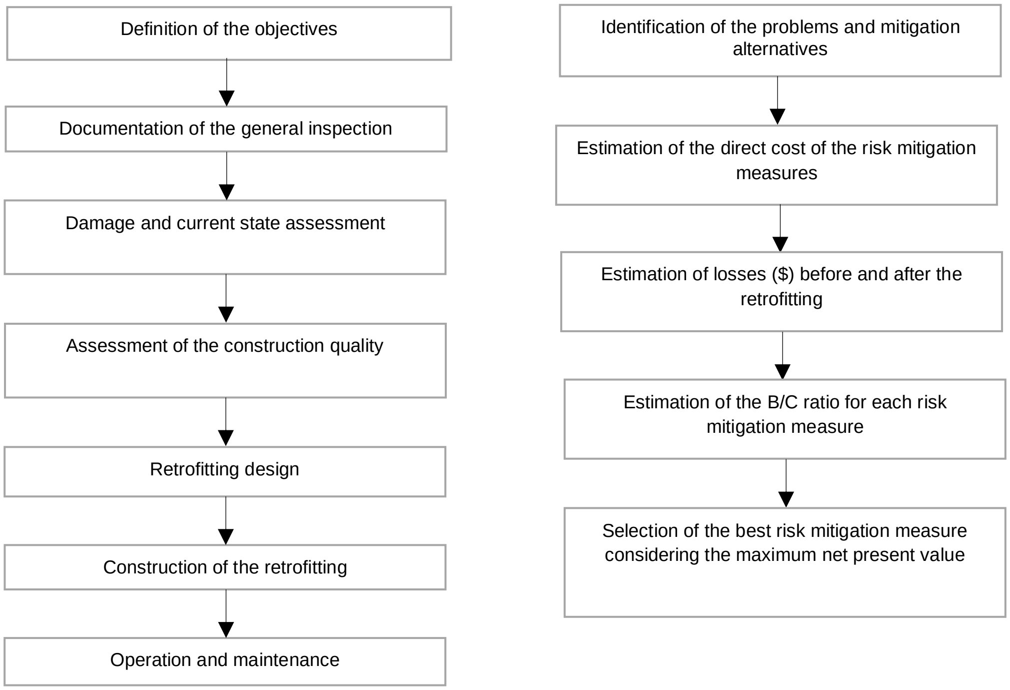


Figure 11. General scheme for identifying a risk mitigation measure. *Source:* Smyth et al. (2004a)

Left: general scheme to identify and use an appropriate risk mitigation measure.

Right: simplified general scheme to select a risk mitigation measure using the BCA

Quantifying the loss reduction (in monetary terms) after implementing a risk mitigation measure is not a simple task. A conceptual approach for estimating that value, when mitigation works are made in infrastructure, is presented next.

As an example, a given portfolio has associated the LEC denoted as “initial state” in Figure 12.

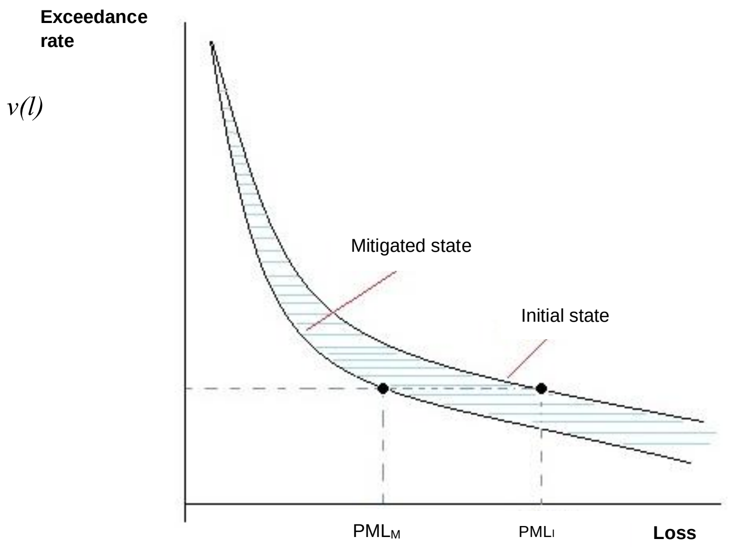


Figure 12. LECs for the initial and mitigated states.

In Figure 12, *v*(*l*) represents the loss exceedance rate, representing the average annual number of times in which a loss with value *l* is exceeded.

From the risk assessment perspective, the effect of implementing risk mitigation measures would be a displacement of the initial state LEC to the left, which is labeled as "mitigated state" in Figure 12. Risk mitigation measures are only possible if there is an available budget, *m*, which should be compared with the benefits of implementing the risk mitigation measure.

There are different ways to measure these benefits. The first one is to select a return period (the inverse value of *v*(*l*)) and consider the benefits of a risk mitigation measure as the difference between the probable maximum loss (PML) in the initial (PML_I) and mitigated states (PML_M). Other option is to compare the AAL reduction with the risk mitigation costs, *m*, properly distributed over time. As per the properties of the LEC, the AAL reduction corresponds to the shaded area in Figure 12.

Clearly, a higher expenditure on risk mitigation would further displace the LEC to the left for the mitigated state, corresponding to a higher reduction of the AAL. The efficiency of this additional expenditure should be compared against the associated reduction in the AAL.

The LEC for both, initial and mitigated states, are to be calculated using a probabilistic risk assessment model - its typical output data are shown in Table 8.

Table 8. Typical results obtained from a probabilistic risk assessment

ID	**Annual occurrence frequency of the scenario**	**Expected loss conditional to the occurrence of the corresponding scenario**	**Variance of the loss conditional to the occurrence of the corresponding scenario**	**Exposed value (usually within the hazard footprint)**
Scenario 1	Annual frequency of scenario 1	$E[L_1 \vert scenario\ 1]$	$Var[L_1 \vert scenario\ 1]$	$Exposed\ value_1$
Scenario 2	Annual frequency of scenario 2	$E[L_2 \vert scenario\ 2]$	$Var[L_2 \vert scenario\ 2]$	$Exposed\ value_2$
Scenario 3	Annual frequency of scenario 3	$E[L_3 \vert scenario\ 3]$	$Var[L_3 \vert scenario\ 3]$	$Exposed\ value_3$
Scenario 4	Annual frequency of scenario 4	$E[L_4 \vert scenario\ 4]$	$Var[L_4 \vert scenario\ 4]$	$Exposed\ value_4$
⋮	⋮	⋮	⋮	⋮
Scenario N	Annual frequency of scenario N	$E[L_N \vert scenario\ N]$	$Var[L_N \vert scenario\ N]$	$Exposed\ value_N$

The information in Table 8 is the following:

- Scenario: a generic description of the event (e.g., location and intensity). It can also be an ID.
- Annual frequency of the scenario: average number of times that the scenario occurs within a year. The annual frequency is not necessarily an integer because it is obtained after dividing the number of times that the event has historically occurred by the number of years of information data. It is important to mention that this variable does not correspond to a probability.

The fact that each scenario accounts for unique locations and intensities, means that the losses are obtained in each case for specific circumstances. If for a given scenario any of these parameters are changed, the resulting losses would be different. The following three outcomes exemplify this:

- Expected loss conditional to the occurrence of the corresponding scenario represents the expected value of the loss after the occurrence of the considered scenario.
- Variance of the loss conditional to the occurrence of the corresponding scenario: it is a dispersion measure that represents how the size of losses associated to the considered scenario differs from its expected value.
- Exposed value: represents the total cost of the exposed assets, usually within the extent of the hazard footprint. It can also be interpreted as the maximum monetary value that can be lost after the occurrence of each scenario.

As mentioned before, the loss exceedance rate has the following mathematical formulation:

$$v(l) = N * \Pr(L > l) \tag{4-1}$$

This expression does not consider the previous occurrence of any scenario, such as the ones included in Table 8, and therefore, the loss is not conditioned to external factors such as the location and/or intensity of the event. This issue does not allow estimating the LEC in a direct manner, but by making the use of some probability axioms.

The main statistical result which is used is the total probability theorem. With it, the probability of any event can be estimated if the conditional occurrence probabilities are known. Its mathematical formulation is the following:

$$\Pr(B) = \sum_{i=1}^{N} \Pr(B|A_i) * \Pr(A_i) \tag{4-2}$$

With this information, this study defines *B* as the case where a loss is higher than a given value, l_i, and A_i as the occurrence of the i^{th} scenario.

When there are data about losses caused by the different scenarios, as shown in the previous tables, results can be sorted by amount, meaning that the number of losses equal to $l_1, l_2, l_3, \ldots . l_N$ (where *N* is the number of scenarios for which loss data are available) would be known. With this, it is also possible to estimate how many losses were higher than any predefined loss value, and the occurrence probability for any of these cases can be estimated as:

$$\text{Occurrence probability of an event} = \frac{\text{number of cases in which the event can occur}}{\text{number of possible cases}} \tag{4-3}$$

In this case, the probability that a loss is equal to a given loss value *l*, is:

$$\Pr(L_i = l) = \frac{\text{number of losses of value } l}{\text{total losses}} \tag{4-4}$$

Similarly, the probability that a loss is higher than a given loss value, *l*, is:

$$\Pr(L_i > l) = \frac{\text{number of losses higher than } l}{\text{total losses}} \tag{4-5}$$

However, there are cases when with detailed studies of how these losses have occurred throughout time, general formulas can be obtained to characterize their behavior. These formulas are known as density functions and their general form is:

$\Pr(X = x) = \mathrm{f}_X(x)$, for any *X*, where *X* is the random variable of interest, in our case, L_i.

It is important to mention that $\Pr(X > x)$ can be expressed as $1 - \Pr(X \leq x) = 1 - \mathrm{F}_X(x)$, where $\mathrm{F}_X(x)$ is known as the cumulative distribution function of *X*.

Regardless of what data are available, it is known that losses are conditional to the occurrence of a hazardous event (i.e. a scenario), so the probability that a loss value is equaled because of one scenario, $\Pr(L_i = l|\text{scenario}_i)$ and the probability that a loss is exceeded because of one scenario, $\Pr(L_i > l|\text{scenario}_i)$ are known. Since the annual occurrence frequency for each scenario, denoted as $\mathrm{F_A}(scenario_i)$, is also known, the occurrence probability of the i^{th} scenario is:

$$\Pr\,(scenario_i) = \frac{\mathrm{F_A}(scenario_i)}{N} \tag{4-6}$$

where *N* is the number of scenarios for which data are available.

With all the information mentioned above, the loss exceedance rate for any loss value can be obtained as:

$$v(l) = N * \Pr(L > l) = N * \textstyle\sum_i \Pr(L > l|I) * f_I(\mathrm{I}) \tag{4-7}$$

$$v(l) = N * \textstyle\sum_i \Pr(L > l|I) * \frac{annual\ frequency\ of\ an\ event\ with\ intensity\ i}{N} \tag{4-8}$$

$$v(l) = \textstyle\sum_i \Pr(L > l|I) * annual\ frequency\ of\ an\ event\ with\ intensity\ i \tag{4-9}$$

Where *N* is the annual number of events (e.g., earthquakes or hurricanes), $P_r(L > l|I)$ is the probability that a determined loss value, l, is exceeded given that an event with intensity i occurs, and $f_I(i)$ is the probability density function for the intensity of a randomly chosen event.

Both *N* and $f_I(i)$ are defined by nature and are not affected by the implementation of a risk mitigation measure. However, $P_r(L > l|i)$ can be subject to modifications after its implementation.

The relationship between the expected loss and a hazard intensity measure (see Table 8) is known as a vulnerability function, which, generally, have the shapes shown in Figure 13.

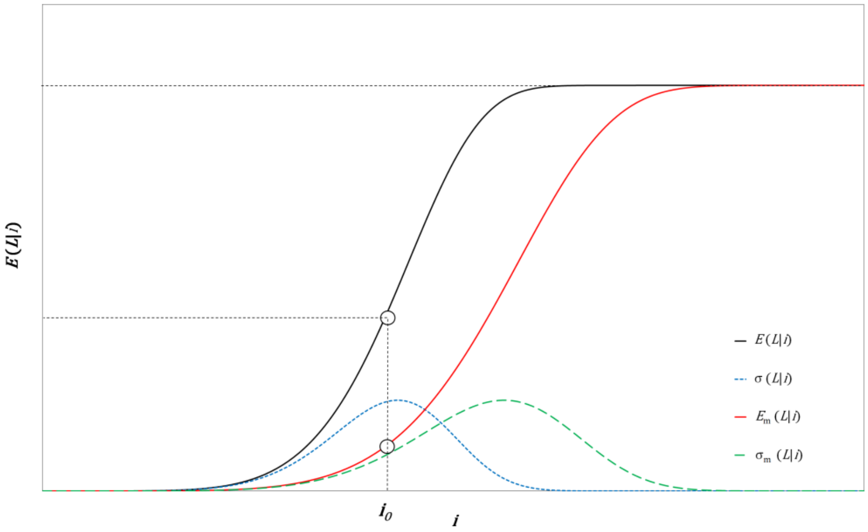


Figure 13. Vulnerability functions of an asset in the initial and mitigated states.

The implementation of a structural risk mitigation measure will modify $E(L|i)$. For example, structural retrofitting can change $E(L|i)$ from its initial form to $Em(L|i)$, as shown in Figure 13 (where *m*, denotes “mitigated state”). In the mitigated state, the expected value of the loss for a given hazard intensity is lower than in the initial state. Therefore, in general terms $P_r(L > l|i)$ will be lower for a value of *I*, meaning that the loss exceedance rate of *l* will also be lower.

It is evident that the efficiency of the investment for *m*, in the variation of the vulnerability functions, depends on the characteristics of the asset(s) under analysis. Also, the efficiency of risk mitigation measures in disaster risk depends not only on the physical vulnerability aspects, but also on the occurrence patterns and rates of catastrophic events, which are mostly defined by nature.

The approaches to measure the benefits of risk mitigation involve knowing risk metrics such as the PML and/or the AAL, both for the initial and mitigated states. This requires developing vulnerability functions for the assets of interest, representing the two states and carrying out the corresponding probabilistic risk assessments. However, the development of physical vulnerability functions is not within the scope of this study.

A methodology to quantify the benefits of implementing risk mitigation measures on infrastructure for earthquakes and floods is needed. One of the solutions to the lack of information to develop this methodology was to develop vectors of generic mitigation measures, so that from a LEC reflecting the initial state, another LEC considering the risk mitigation measures can be obtained.

A comprehensive documentation of the main parameters that are commonly involved in the implementation of mitigation measures in disaster risk reduction was made. A summary with all details is presented in the following section.

4.2 TECHNICAL APPROACH TO MITIGATION

To estimate the benefits of a risk mitigation measure, it is necessary to have all detailed and relevant data on its characteristics (e.g., cost, construction characteristics and structural implications, among others), together with detailed information on damages before and after the implementation of these measures. This can allow to observe the differences between the initial and mitigated states and to estimate their costs and benefits in an accurate manner.

This approach is often used for specific constructions at given locations but having this information at national or sub-national level, remains being a challenge for the LAC countries because of the lack of information. Instead, proxy approaches, based on bibliographic information and expert criterion can be used, as in this study.

The following publications are used in this study to account for BCA approaches in specific types of infrastructure within the context of risk mitigation: Kappos et al. (1995), Thiel and Hagen (1998), Mechler (2005), Kappos and Dimitrakopoulos (2008), Valcárcel et al. (2011), Liel and Deierlein (2013) and Pomonis and Gaspari (2014). Additionally, BCA requires to measure the costs associated to hazard and risk mitigation in terms of all used (or destroyed) resources, besides using prices that represent an efficient allocation. Within the scope of this study, literature reviewed documented the following relevant data regarding the implementation of risk mitigation measures:

- Ratio of the cost of implementing the risk mitigation measure with respect to the initial cost of the asset (or its replacement cost before implementing the risk mitigation measure), expressed as a percentage.

$$C_{M/I}(\%) = \frac{Mitigation\ Measure\ Cost}{Cost\ of\ Property} * 100 \tag{4-10}$$

- As previously mentioned, a commonly used metric in the analyses for the implementation of mitigation measures is the B/C ratio. Depending on the bibliographic references, it can be found in two ways. First, as the ratio between the benefit (i.e. loss reduction or avoided loss) obtained after implementing the risk mitigation measure with respect to its implementation cost and, secondly, as the ratio between the same benefit with respect to the exposed value. For this study, the first definition will be used:

$$\frac{B}{C} ratio = \frac{Benefit\ of\ implementing\ a\ risk\ mitigation\ measure}{Cost\ of\ the\ measure} \tag{4-11}$$

- Another relevant metric is the loss reduction percentage after implementing a risk mitigation measure, with respect to the loss for the initial state. This concept is schematically shown in Figure 14 and with this value, it is possible to determine the variation of losses after implementing a risk mitigation measure if compared with the measure in its initial state.

$$P_{R/I}(\%) = \frac{Loss\ reduction}{Loss\ without\ mitigation} * 100 \tag{4-12}$$

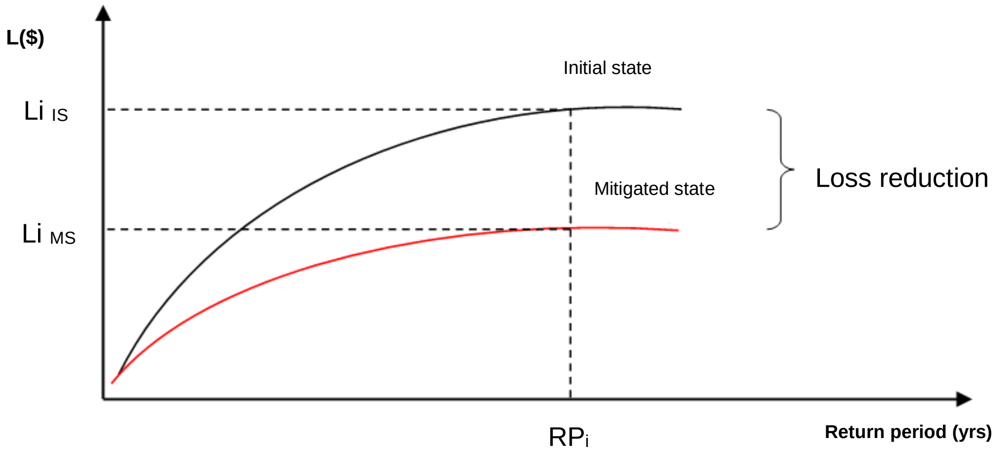


Figure 14. Loss vs. return period plots before and after implementing a risk mitigation measure.

In Figure 14, Li_{IS} and Li_{MS} correspond to the initial and mitigated states losses, respectively, associated to a given return period, RP_i (in years).

4.3 REPRESENTATIVE RISK MITIGATION MEASURES FOR EARTHQUAKES

FEMA performed a BCA with about 5,500 samples assigned for risk mitigation measures between 1993 and 2003 (Rose et al., 2007). This analysis included projects with structural retrofitting (e.g., base isolation of public buildings), non-structural improvements (e.g., retrofitting of hanging lamps in schools), drafting and enforcement of building codes, and hazard mitigation (intervention) plans, among others. Overall, B/C ratios of 4.0 for earthquake, wind and flood perils were found, with total benefits of around US$ 14.0 billion, and associated costs of around US$ 3.5 billion (Rose et al., 2007).

Error! Reference source not found. shows the results of that study, including the e stimated benefits and costs for earthquakes and other hazards. The B/C ratio for earthquake is 1.5, for wind is 3.9 and for flood is 5.0. The results of the study developed by Rose et al. (2007) concludes that the B/C ratio is always higher than 1.0.

Table 9. Benefits and costs reported for different hazards in the USA

Hazard	Cost (US$ Million)	Benefit (US$ Million)	B/C ratio (See equation 4-11)
Earthquake	947	1,392	1.5
Wind	374	1,468	3.9
Flood	2,217	11,189	5.0
TOTAL	**3,538**	**14,049**	**4.0**

Source*:* Rose et al. (2007)

When a risk mitigation measure is implemented, in addition to the expected reductions in economic losses, human losses are also expected to be reduced.**Error! Reference source not found.** indicates a decrease of 4,699 injuries and 223 fatalities because of the risk mitigation activities over their lifetime, for which the return period was set in most cases to 1/50 years.

Table 10. Estimated reduction of injuries and fatalities after implementing risk mitigation measures

Hazard	Injuries	Fatalities
Earthquake	1,399	67
Wind	1,510	0
Floods	1,790	156
TOTAL	**4,699**	**223**

Source: Rose et al. (2007)

B/C ratios tend to fluctuate depending on the type of analysis that is used for its quantification. Parameters such as the amortization period, the discount rate, the cost of lives (if considered), and the number of exposed inhabitants, among others can significantly affect the results. Besides these parameters, the structural system, the hazard level and the risk mitigation measure to be implemented can also influence the results.

The following section introduces different risk mitigation measures in different types of infrastructure, based on the available literature. The main objective of this task is to identify typical values for the required parameters.

4.3.1 BCA for earthquake risk reduction: structural retrofitting of hospitals

Rose et al. (2007) included a BCA for the structural retrofitting of a hospital to reduce earthquake risk. In their study, the risk assessments with and without considering the structural retrofitting were performed using the HAZUS®MH tool. The comparison metric was the AAL, thus obtaining its B/C ratio. The structural retrofitting consisted in improving the earthquake load resistance system of the hospital.

Tables 11 to 15 show the characteristics and results of the hospital in this study, where the initial structural system consisted of reinforced concrete shear walls and the mitigation measure consisted of retrofitting the structure to comply with the current building code's requirements. Total benefits were equal to US$ 40 million and the mitigation implementation costs were US$ 30 million, yielding a B/C ratio of 1.3. In this case, the value of lives was considered and an amortization period of 100 years together with a discount rate of 2%.

Table 11. Comparison of key characteristics between initial and mitigated states

Building characteristics	**Initial state**	**Mitigated state**
Use	Hospital	Hospital
Structural system	Reinforced concrete shear walls	Reinforced concrete shear walls
Design level	Poor	High
Building quality	Pre-building code	As per the building code

Source: COUNCIL, Multi-hazard Mitigation (2005)

Table 12. Annualized losses for the initial and mitigated states

Annualized losses	**Initial state (US$)**	**Mitigated state (US$)**
Capital loss of the building	235,608	74,860
Direct losses because of business interruption	412,968	69,083
Subtotal (US$)	648,576	143,943
Claims value	151,343	1,435

Source: COUNCIL, Multi-hazard Mitigation (2005)

Table 13. Annualized benefits of implementing a risk mitigation measure

Annualized benefit (US$)	
Reduced capital loss of the building	160,748
Direct reduced loss because of business interruption	343,885
Reduced environmental loss	38
Reduced loss	149,908

Source: COUNCIL, Multi-hazard Mitigation (2005)

Table 14. Benefits and costs for the project in 1997 USD

Benefit and Costs in the Project Year (1997) US$	
Amortization period	100 years
Discount rate (without claims)	2%
Reduced capital loss of the building	$6,927.974
Direct reduced loss because of business interruption	$14,828.877
Reduced environmental loss	$1.638
Reduced loss due to claims	$12,618.519
Cost	$26,449.484

Source: COUNCIL, Multi-hazard Mitigation (2005)

Table 15. Benefits and costs for the project in 2004 USD

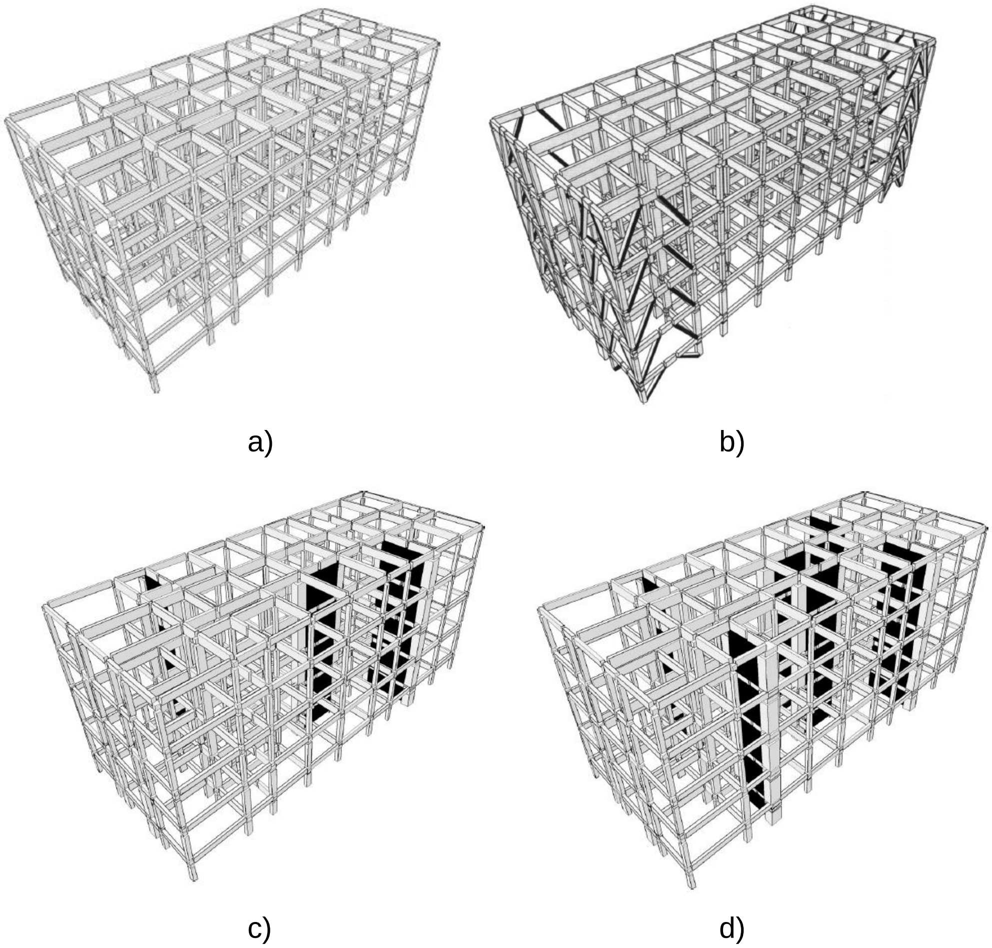
Benefits and Costs in 2004 US$	
CPI 2004/CPI 1997	1.188
Reduced capital loss of the building	$8,230.433
Direct reduced loss because of business interruption	$17,607.201
Reduced environmental loss	$1.946
Reduced loss due to claims	$14,990.800
Total benefit	$40,830.380
Cost	$31,421,987
B/C ratio	1.30

Source: COUNCIL, Multi-hazard Mitigation (2005)

4.3.2 Structural retrofitting of residential buildings to mitigate earthquake risk

Smyth et al. (2004a) carried out a “*Probabilistic benefit-cost analysis for earthquake damage mitigation: Evaluating measures for apartment houses in Turkey*” study which includes case studies developed in Istanbul, Turkey. The selected building for the analysis was built in 1968 and is a typical five-story residential building, with reinforced concrete frames as the structural system. Authors considered different timeframes (1, 2, 3, 4, 5, 10, 25 and 50 years), from which it is possible to select a representative timeframe for the lifetime of the structure (e.g., 25 or 50 years). The discount rate used in this study is 3%.

The initial state of the building was also considered. A schematic representation of the earthquake risk mitigation measures proposed by the authors are shown in Figure 15


a) b)

c) d)

Figure 15. Initial state and possible retrofitting options. Source*:* Smyth et al. (2004a)
a) Initial state, b) Introduction of structural braces, c) Partial retrofitting with reinforced concrete shear walls d) Full retrofitting with reinforced concrete shear walls

Table 16 shows the values for the property costs, together with those associated to each of the considered mitigation measures that seek to reduce earthquake risk. Besides this, the values of expected damages and benefits are also included, where the latter are obtained after subtracting the expected damage after implementing the corresponding risk mitigation measure from the expected damage in the initial state.

Table 16. Values for the earthquake risk mitigation measures for residential buildings in Turkey

Property cost (US$)	Mitigation measure	Cost of the risk mitigation measure (US$)	Expected damage (US$)	Expected benefit after mitigation (US$)
250,000	No mitigation measure	-	39,400	-
	Structural braces	65,000	22,900	16,500
	Partial placement of shear walls	80,000	7,600	31,800
	Full placement of shear walls	135,000	2,100	37,300

Source : Smyth et al. (2004a)

The information included in Table 16 allows to calculate the percentage of the cost of mitigation measures, with respect to the cost of the property ($C_{M/P}$), and the percentage of the loss reduction, with respect to the initial state loss ($L_{R/I}$). The B/C ratio was obtained by dividing the expected benefit after implementing a risk mitigation measure into its implementation cost. Table 17 shows the obtained results.

Table 17. Cost, loss and B/C ratios for the analyzed buildings in Turkey

Mitigation measures	$C_{M/P}$ (%)	$L_{R/I}$ (%)	B/C ratio
Structural braces	26.0	41.9	0.25
Partial placement of shear walls	32.0	80.7	0.40
Full placement of shear walls	54.0	94.7	0.28

According to Smyth et al. (2004a), the implementation of risk mitigation measures has additional benefits that are beyond the reduction of physical damages and losses in buildings. One of these additional benefits (and perhaps the most important one) is the reduction of impacts on people who inhabit the retrofitted properties (e.g., reduction in the number of casualties).

Michel-Kerjan et al. (2013) went one step further and in their study, "*Catastrophe risk models for evaluating disaster risk reduction investment in developing countries*" and used the results of Smyth et al. (2004a) as a starting point, adding some variables that are representative to constructive typologies in Istanbul, Turkey.

Because of the 1999 earthquake in Kocaeli, Turkey, many buildings with similar characteristics to those analyzed by Smyth et al. (2004a) collapsed, mainly because their columns did not have an adequate quantity of reinforcing steel to withstand the lateral loads imposed by the earthquake. Also, many of these buildings had been designed with an open lower floor, destined for other uses other than residences, such as parking spaces, therefore having a "soft-story" (as known in structural engineering) which decreases the structural performance under earthquake loads. Another constructive detail that contributed to the failure of the columns and the collapse of the buildings, was the distance between the columns and the walls, that reduces the effective height of the columns, causing the "short column" problem.

Michel-Kerjan et al. (2013) analyzed the building proposed by Smyth, A. et al. (2004a) and its three types of structural retrofitting alternatives, to which two additional structural characteristics were added, such as the existence of soft-story and short column conditions, to determine whether structural retrofitting was needed.

Table 18 shows the three types of analyzed structures and their possible combinations. According to the vulnerability analyses, Type 1 and Type 3 buildings are about 4% and 14% more vulnerable than Type 2 buildings, respectively.

Table 18. Types of structures and combinations considered

Typology	**Soft-story (S-S)**	**Short column (S-C)**	**Retrofitting needed?**
Type 1	Yes	No	Yes
Type 2	No	Yes	Yes
Type 3	Yes	Yes	Yes

Source : Michel-Kerjan et al. (2013)

The following risk mitigation measures were proposed by the authors to reduce the seismic risk in the building:

- Retrofit the short column and/or the soft story without adding reinforced concrete shear walls.
- Add some reinforced concrete shear walls and retrofit the short columns, if applicable.
- Add several reinforced concrete shear walls and retrofit the short columns, if applicable.

Table 19 shows the costs associated to each of the proposed risk mitigation measures, applicable to each of the considered building typologies.

Table 19. Cost of implementing the alternatives for each building typology

Mitigation measures	**Cost (US$)** **Type 1**	**Cost (US$)** **Type 2**	**Cost (US$)** **Type 3**
Mitigation in SC and SS	25,000	40,000	65,000
Mitigation in SC and PSW	80,000	120,000	120,000
Mitigation in SC and FSW	135,000	175,000	175,000

** SS = Soft-story, SC = Short column, PSW= Partial placement of shear walls,*

FSW = Full placement of shear walls

Source : Michel-Kerjan et al. (2013)

For the BCA, two discount rates (5% and 12%) and two lifetimes for the buildings (25 and 50 years) were used. The B/C ratio yields values between 0.00 to 0.28 (see Table 20), which means that despite the earthquake hazard level, the timeframe and the discount rate used, the costs of implementing the three mitigation measures outweigh their benefits. From a purely financial perspective, this means that such risk mitigation measures are not profitable.

Table 20. B/C ratios for buildings in the Provinces of Atakoy and Camlicahce

Mitigation measure	**Lifetime (years)**	**Type 1**				**Type 2**				**Type 3**			
		Maximum B/C in Atakoy		**Minimum B/C in Camlibahce**		**Maximum B/C in Atakoy**		**Minimum B/C in Camlibahce**		**Maximum B/C in Atakoy**		**Minimum B/C in Camlibahce**	
		Discount rate		**Discount rate**		**Discount rate**		**Discount rate**		**Discount rate**		**Discount rate**	
		5%	12%	5%	12%	5%	12%	5%	12%	5%	12%	5%	12%
Mitigation in SC and SS	25	0.22	0.12	0.02	0.01	0.09	0.05	0.01	0.00	0.14	0.08	0.01	0.01
	50	0.28	0.13	0.02	0.01	0.12	0.05	0.01	0.00	0.18	0.08	0.01	0.01
Mitigation in SC/PSW	25	0.22	0.12	0.01	0.01	0.09	0.05	0.01	0.00	0.12	0.07	0.01	0.00
	50	0.25	0.13	0.02	0.01	0.12	0.05	0.01	0.00	0.16	0.07	0.01	0.00
Mitigation in SC/FSW	25	0.11	0.06	0.01	0.00	0.06	0.03	0.00	0.00	0.11	0.06	0.01	0.00
	50	0.15	0.07	0.01	0.00	0.08	0.04	0.01	0.00	0.14	0.06	0.01	0.00

** SS = Soft-story, SC = Short column, PSW= Partial placement of shear walls,*

FSW = Full placement of shear walls

Source : Michel-Kerjan et al. (2013)

However, the picture changes when the value of life is included in the analysis. For the USA and for some European countries, the value of a life has been appraised between US$1 and

US$10 million (Michel-Kerjan et al. 2013). These values can vary a lot depending on living conditions for a citizen of a country and is closely related to its development level. For Turkey, authors used US $750,000 as the value of one life.

In the case of structural retrofitting with steel braces (Type 1 building) and the value of life mentioned above, the B/C ratio is higher than 1.0 when using a discount rate of 5%. If for instance, the value of life is increased to US$6 million, with the same discount rate, the B/C ratios increase 8 and 10, for lifetimes of 25 and 50 years, respectively, making thus the investment highly attractive. Table 21 summarizes the results obtained by the authors.

Table 21. B/C ratios considering the value of life for Type 1 building and mitigation measure 1

Analysis considering different *VLS	**Lifetime (years)**	**B/C ratio**	
		Discount rate	
		5%	**12%**
*VSL = 750,000 US$	25	1.3	0.7
	50	1.6	0.73
*VSL = 6,000,000 US$	25	8.1	4.6
	50	10.8	4.9

*VSL = Value of statistical life

Source : Michel-Kerjan et al. (2013)

The results documented by the studies presented above suggest that the value of lives is an important factor to include in these types of analyses. It is also evident that, depending on the country, this statistical value of lives can vary considerably, in the way that is commonly appraised by economists.

4.3.3 Schools

Smyth et al. (2004b) analyzed a two-story school, with a structural system consisting on reinforced concrete frames with eight bays in the longitudinal direction and one bay in the perpendicular one. This school typology is common in Latin American countries, such as in Mexico, and is considered to be representative. Figure 16 shows some illustrative photographs for this building typology.

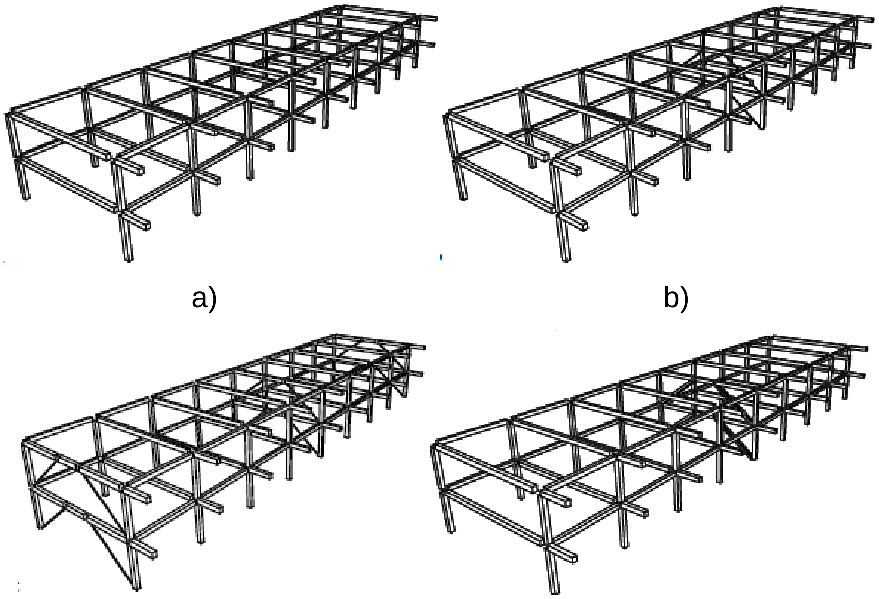
Source: Smyth et al. (2004b)

Figure 16. Typical schools in Mexico.

To perform the BCA, the authors proposed three risk mitigation measures, which are:

- Placement of steel braces in the middle bay
- Placement of steel braces in the middle and lateral bays
- Placement of reinforced concrete braces

Figure 17 shows the schemes corresponding to the structure in the initial state and the three considered risk mitigation measures. It can be noted that the structural systems chosen by Smyth et al. (2004b) to retrofit the structure have to do, in all cases, with the placement of braces either made of steel or in reinforced concrete.



a) b)

c) d)

Figure 17. Initial state and proposed risk mitigation measures. Source: Smyth et al. (2004b)

a) Initial state, b) First steel bracing option, c) Second steel bracing option and d) Reinforced concrete braces

Table 22 shows the implementation costs for each of the proposed risk mitigation measures, together with the results in terms of their expected benefits. Benefits were obtained based on the net present value and the cost of each risk mitigation measure, as reported by Smyth et al. (2004b).

The authors analyzed different lifetimes for the buildings. Table 22 shows the results obtained for 50 years, which is representative for these type of buildings. A social discount rate of 3% was used and it was assumed that 15 fatalities would occur if the building collapses, assigning to each life a value of US$ 400,000.

Table 22. Results of the risk mitigation measures for schools

Cost of the school (US$)	**Mitigation measure**	**Cost of implementing the measure (US$)**	**Expected benefit because of the mitigation measure (US$)**
160,000	Steel braces (option 1)	8,000	57,344
	Steel braces (option 2)	20,000	95,016
	Reinforced concrete braces	13,000	96,238

Source *:* Smyth et al. (2004b)

Table 23 shows the cost of the mitigation measures with respect to the cost of property ($C_{M/P}$) as a percentage. In this case, the percentage of the loss reduction with respect to the loss in the initial state ($L_{R/I}$) could not be estimated because the value of the initial loss (without mitigation) is not reported in the study. The B/C ratios obtained for this case have values between 4.8 and 7.4, which are indicative of the many benefits of implementing risk mitigation measures in critical infrastructure, such as schools, where it is also relevant to reduce the impacts of these type of events to the occupants of the structure.

Table 23. Parameters obtained after the data of the study of schools

Mitigation measures	**$C_{M/P}$ (%)**	**$P_{R/O}$ (%)**	**B/C ratio**
Steel braces (option 1)	5.0	-	7.2
Steel braces (option 2)	12.5	-	4.8
Reinforced concrete braces	8.1	-	7.4

Source*:* Self-elaborated after data by Smyth et al. (2004b)

4.3.4 Offices

Thiel and Hagen (1998) focused their study on three buildings that suffered damages after the 1994 Northridge earthquake in California. Two of these are 10-story buildings mainly used for office space, whereas the third building is a three-story structure that served as a parking facility. Depending on the observed damage levels, several repair schemes were considered. For the purposes of this study, we will consider these repair schemes as the risk mitigation measures.

Of the cases considered by the authors, this study focused on buildings A and B - the 10-story buildings. The total present value of the costs of the mitigation measures estimated by the authors account for the initial cost of the risk mitigation measure and the present value of the damages caused by a future earthquake after using a discount rate. Since the types of damages are different depending on the characteristics of each building, the repair schemes are also different. The timeframes considered by the authors were 20 and 50 years, using also two discount rates of 4% and 8%. The results summarized herein correspond to the case of 50 years for the timeframe and 4% for the discount rate. Table 24 shows the results after Thiel and Hagen (1998) for the property cost, the type of risk mitigation measure, its implementation cost and the total present value.

Table 24. Property cost, mitigation cost and total present value for the considered mitigation measures

Property cost (US$)	Mitigation measures	Mitigation cost (US$)	Total present value (US$)
19,100,000	A_1: Repair all damage to elements to the same condition prior to the earthquake	6,830,000	10,000,000
	A_2: Repair and retrofit the 4 most damaged frames and repair all the remaining damages to connections to the same condition prior to the earthquake	8,870,000	11,170,000
	A_3: Repair and retrofit all connections in all the frames of the structure	14,480,000	15,660,000
	A_4: Add dampers in selected bays from the bottom to the top and repair all damage to connections to the same condition prior to the earthquake	8,380,000	9,970,000
21,800,000	B_1: Repair all damages to elements to the same condition prior to the earthquake	2,910,000	6,900,000
	B_2: Repair and retrofit all connections in the 4 most damaged frames and repair all the remaining damages in connections to the same conditions prior to the earthquake	5,000,000	7,720,000
	B_3: Repair and retrofit all connections in all the frames of the structure	9,580,000	10,930,000
	B_4: Add dampers in selected bays from the bottom to the top and repair all damage to connections to the same condition prior to the earthquake.	4,430,000	6,240,000

Source*:* Thiel and Hagen (1998)

From results in Table 24, it is possible to consider that repair schemes A_1 and B_1 correspond to reaching the same structural conditions of the building prior to the occurrence of the earthquake (i.e. without the implementation of a risk mitigation measure). Additionally, since the total present value reported in Table 24 corresponds to the sum of the cost of the mitigation measure and the present value of the damage caused by a future earthquake, it is possible to estimate the latter value by considering different risk mitigation measures, which in turn would allow to estimate the expected benefits in terms of the reduction of future losses, as shown in Table 25.

Table 25. Values for the present cost of damages and benefits for the different mitigation measures

Mitigation measures	Present value of damage because of a future earthquake (US$)	Benefit in damage reduction for a future earthquake (US$)
A_1	3,170,000	0
A_2	2,300,000	870,000
A_3	1,180,000	1,990,000
A_4	1,590,000	1,580,000
B_1	3,990,000	0
B_2	2,720,000	1,270,000
B_3	1,350,000	2,640,000
B_4	1,810,000	2,180,000

Source*:* Thiel and Hagen, (1998)

Table 26 shows the cost of the risk mitigation measures with respect to the cost of property ($C_{M/P}$), as a percentage, and the loss reduction with respect to the initial loss ($L_{R/I}$), also as a percentage. Finally, the B/C ratio is also included, corresponding to the benefit of reducing damages for a future earthquake divided by its implementation cost.

Table 26. Cost mitigation effectiveness and B/C ratio for the considered risk mitigation measures

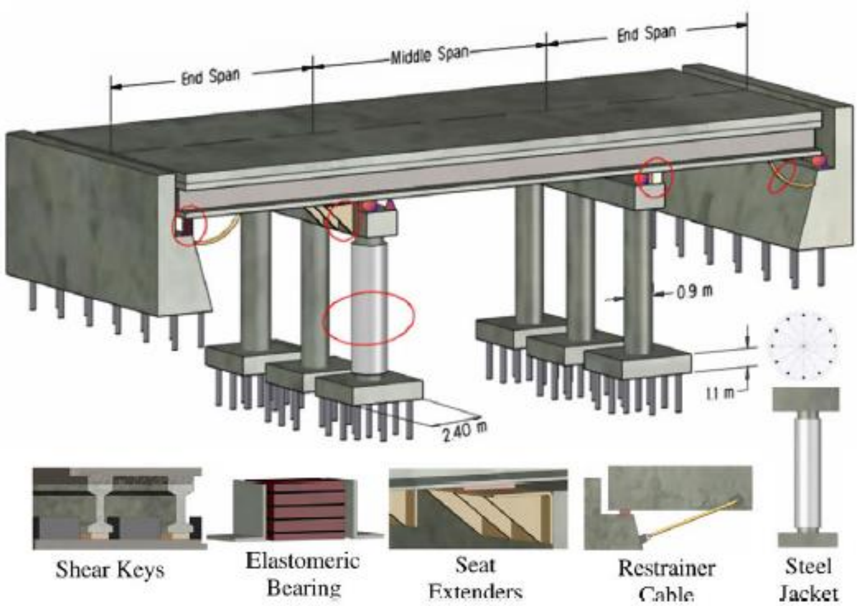
Mitigation measure	$C_{M/P}$ (%)	$L_{R/I}$ (%)	B/C ratio
A_1	36	0.0	0.00
A_2	46	27	0.10
A_3	76	63	0.14
A_4	44	50	0.19
B_1	13	0.0	0.00
B_2	23	32	0.25
B_3	44	66	0.28
B_4	20	55	0.49

Source*:* Thiel and Hagen (1998)

4.3.5 Bridges

Dennemann (2009) and Padgett et al. (2010) proposed a Life-Cycle Cost (LCC) analysis for bridge modelling, which includes all costs of the initial construction, maintenance and repairing. In addition, it considers possible earthquake damages, among other factors, expressed in monetary units at present value. Both studies consider four different types of bridges (two made of steel and two made of reinforced concrete) with different structural configurations located in the USA.

Different alternatives were assumed as risk mitigation measures, as shown in Figure 18, together with combinations amongst them. The analyses were performed in different states of the USA to understand how the earthquake hazard levels were related to the B/C results.



Source*:* Padgett et al. (2010)

Figure 18. Risk mitigation options for a reinforced concrete bridge with several spans.

For this study, the results obtained for Caruthersville, Missouri, a location near the seismic prone area of New Madrid, were considered of interest. Figure 19 shows pictures of the five risk mitigation measures, some of which were implemented at the design phase of a bridge, because of their importance in its structural behavior.

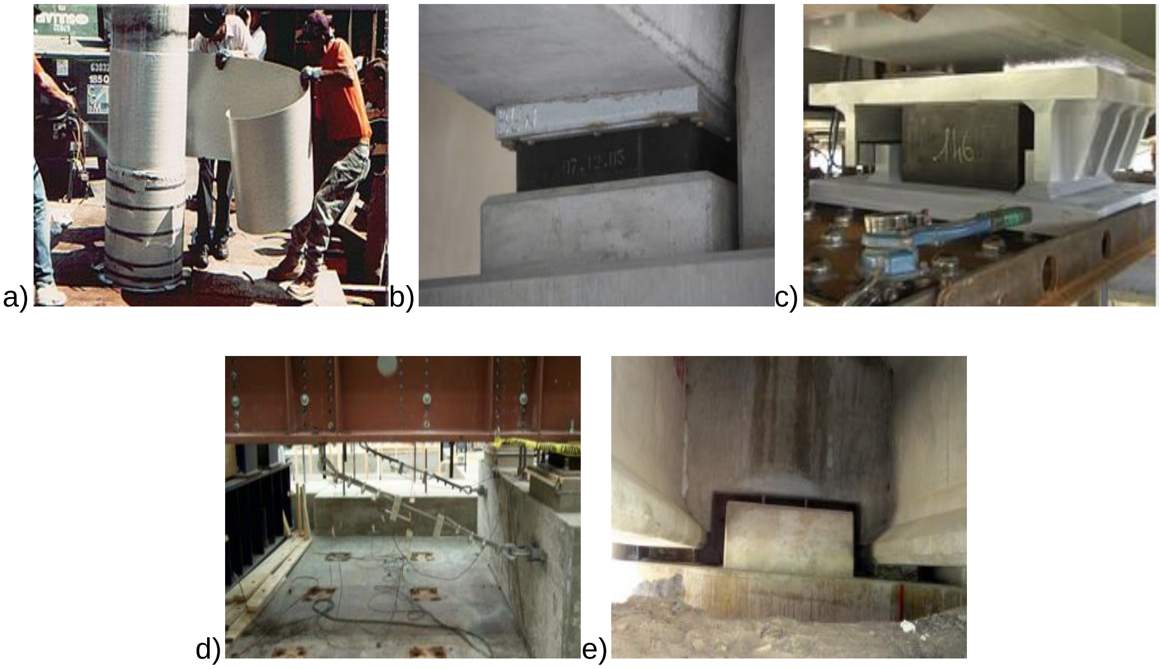


Figure 19. Example of risk mitigation measures in bridges. Source: own photographs
a) Steel jacket b) Elastomeric bearings c) Shear keys d) Restrainer cable
e) Seat extender

Table 27 shows the proposal for seven risk mitigation measures that are associated to different sections of the bridges, together with their costs (the last two alternatives are a combination of individual measures). Similarly, the expected loss is also shown, obtained using the LCC procedure in US$ dollars in the present time with a 50-years probability. The benefit corresponds to a reduction of the expected cost, which corresponds to the expected cost of the damages in the initial state (i.e. without the mitigation measure) minus the expected cost of damages after having implemented the mitigation measure. The choice of the mitigation measure will depend on the damage level of the bridge and its earthquake hazard level.

Table 27. Data for a bridge in Caruthersville, Missouri

Cost of Property (US$)	Mitigation Measures	Mitigation Cost (US$)	Expected loss (US$)	Benefit (US$)
438,237	Initial state	-	91,915	-
	a) Steel jacket	36,000	79,051	12,864
	b) Elastomeric bearings	21,912	65,760	26,155
	c) Shear keys	9,000	76,601	15,314
	d) Restrainer cable	11,280	87,101	4,841
	e) Seat extender	23,250	91,251	664
	f) Shear keys + seat extender	32,250	76,639	15,276
	g) Restrainer cable + seat extender	34,530	84,123	7,792

Source*:* Dennemann (2009)

Table 28 shows the cost of the risk mitigation measures with respect to the cost of the bridge ($C_{M/P}$), as a percentage, and the loss reduction with respect to the initial loss ($L_{R/I}$) also as a percentage, together with the B/C ratio. The B/C ratio is estimated by dividing the reduction in the expected loss, for each mitigation measure, by their implementation cost. The study by Dennemann (2009) does not specify if human losses were considered (i.e. number of lives saved and their cost), neither the amortization rate that was used.

Table 28. Effectiveness of the implementation of mitigation measures in bridges

Mitigation measures	$C_{M/P}$ (%)	$L_{R/I}$ (%)	B/C ratio
a) Steel jacket	8.2	14.0	0.36
b) Elastomeric bearings	5.0	28.5	1.19
c) Shear keys	2.1	16.7	1.70
d) Restrainer cable	2.6	5.3	0.43
e) Seat extender	5.3	0.7	0.03
f) Shear keys + seat extender	7.4	16.6	0.47
g) Restrainer cable + seat extender	7.9	8.5	0.23

4.4 REPRESENTATIVE RISK MITIGATION MEASURES FOR FLOODS

Floods are a type of natural hazard that has caused large human losses. Data by the International Committee on Large Dams (ICOLD) indicate that most of these fatalities have occurred in Asian countries, as shown in Table 29.

Table 29. Annual number of fatalities caused by floods

Fatalities	Countries
0-10	Argentina, Australia, Brazil, Canada, France, Ireland, Italy, Netherlands, Norway, South Africa, Switzerland and Russia.
10-20	Spain
50-100	Indonesia and the United States of America
100-150	Japan
>150	South Korea (250), Bangladesh (200), India (1500) and China (2000-3000).

Source*:* (ICOLD, 2003)

Among the set of flood BCA published by the IBI Group (2015), the following risk mitigation measures were considered for the city of Calgary, in Canada:

1) Construction of an earth dam along the main branch of the Elbow River, including a concrete landfill for the discharge of normal water flows and floods, as shown in Figure 20 (denoted as mitigation measure MC1).
2) Construction of a reinforced concrete overflow section through the Elbow River, also of a drain located on the left side of the abutment reversing the level of the river's thalweg (see Figure 21) and finally, a closed diversion structure, located on the left side of the abutment, immediately upstream of the drain (denoted as mitigation measure SR1).
3) In the event of a flood exceeding a return period equal to or longer than 100 years, flood water will flow through a 4.2km tunnel along the Heritage Drive (strategic location for this work in Calgary), as shown in Figure 22.

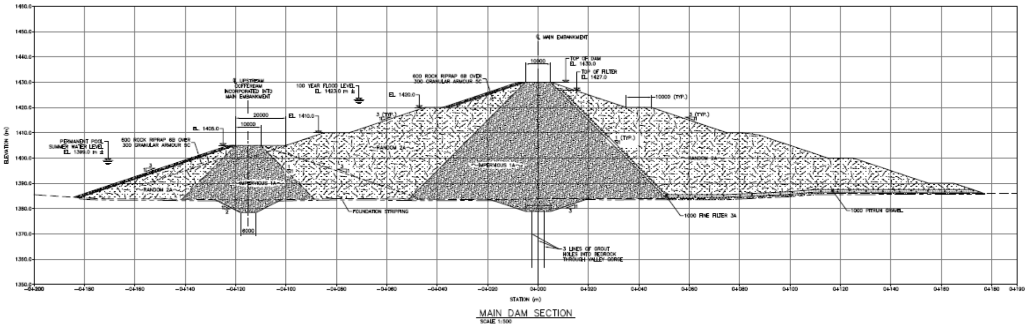


Figure 20. Illustrative scheme for the MC1 mitigation measure. Source: IBI Group, (2015)

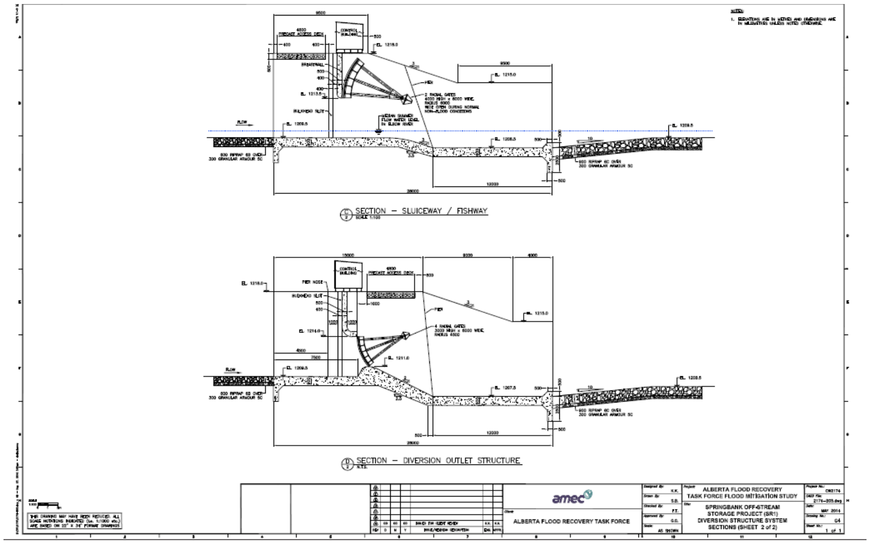
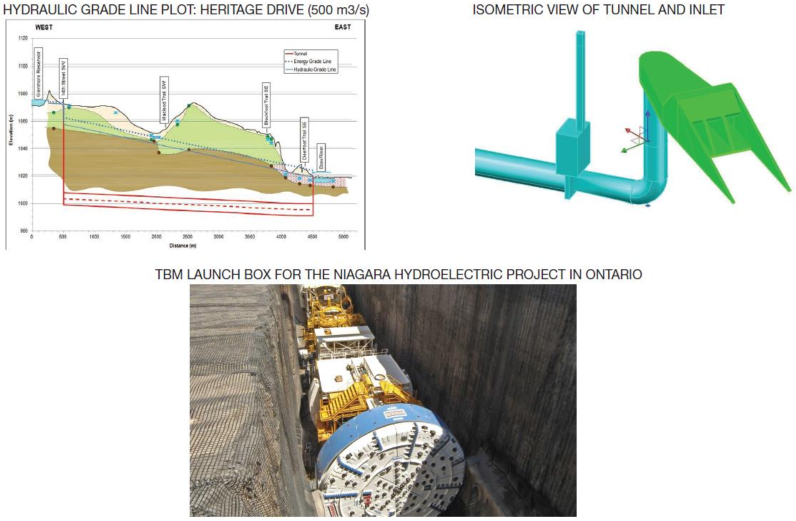


Figure 21. Illustrative scheme for the SR1 mitigation measure. Source: IBI Group, (2015)


HYDRAULIC GRADE LINE PLOT: HERITAGE DRIVE (500 m3/s)

ISOMETRIC VIEW OF TUNNEL AND INLET

TBM LAUNCH BOX FOR THE NIAGARA HYDROELECTRIC PROJECT IN ONTARIO

Figure 22. Illustrative scheme for the tunnel mitigation measure. Source: IBI Group, (2015)

Table 30 shows the summary of construction, relocation and annual protection costs for 100 and 200-year return periods. Tables 31, 32 and 33 show the results of the BCA for the risk mitigation measures proposed for Calgary.

Table 30. Cost of the considered risk mitigation measures in Calgary, Canada

Description	MC1 (US$)	SR1 (US$)	Tunnel (US$)
Construction cost	39,581,000	159,768,000	458,600,000
Upstream mitigation	-----------------------	-----------------------	8,900,000
Infrastructure relocation	45,000,000	8,900,000	-----------------------
Environmental impact studies	4,000,000	40,000,000	-----------------------
Total cost for 100-yr return period annual protection	288,581,000	208,668,000	467,500,000
Additional cost for 200-yr return period annual protection	55,000,000	55,000,000	39,600,000
Total cost for 200-yr return period annual protection	343,581,000	263,668,000	507,100,000
Annual cost of operation and maintenance	1,800,000	1,800,000	1,800,000

Table 31. Summary of the BCA for MC1

Indicator	Greatest damage scenario		Least damage scenario	
	Protection 100-years (US$)	Protection 200-years (US$)	Protection 100-years (US$)	Protection 200-years (US$)
PV of the benefits (Average annual damage)	476,899,000	639,943,000	336,847,000	408,901,000
PV of the costs (development and total operating costs)	332,708,000	387,699,000	332,708,000	387,699,000
B/C ratio	1.43	1.65	1.01	1.05
NPV	144,191,000	252,244,000	4,139,000	21,202,000
AAL	19,461,291	26,114,777	13,746,068	16,686,439

*PV: Present value

Source: IBI Group, 2015

Table 32. Summary of the BCA for SR1

Indicator	Greatest damage scenario		Least damage scenario	
	Protection 100-years (US$)	Protection 200-years (US$)	Protection 100-years (US$)	Protection 200-years (US$)
PV of the benefits (Average annual damage)	476,899,000	639,943,000	336,847,000	408,901,000
PV of the costs (development and total operating costs)	255,098,000	309,607,000	255,098,000	309,607,000
B/C ratio	1.87	2.07	1.32	1.32
NPV	221,801,000	330,336,000	81,749,000	99,294,000
AAL	19,461,291	26,114,777	13,746,068	16,686,439

*PV: Present value

Source*:* IBI Group, 2015

Table 33. Summary of the BCA for the tunnel

Indicator	Greatest damage scenario		Least damage scenario	
	Protection 100-years (US$)	Protection 200-years (US$)	Protection 100-years (US$)	Protection 200-years (US$)
PV of the benefits (Average annual damage)	621,715,000	664,189,000	416,313,000	458,787,000
PV of the costs (development and total operating costs)	512,465,000	551,960,000	512,465,000	551,960,000
B/C ratio	1.20	1.20	0.81	0.83
NPV	109,250,000	112,229,000	-96,152,000	-93,173,000
AAL	25,370,933	27,104,222	16,988,895	18,722,184

*PV: Present value

Source*:* IBI Group, 2015

The study developed by Jha et al. (2012) summarized the benefits, costs and B/C ratio related to flood risk management for different locations. One example is the Kailali Disaster Reduction Initiative (KDRRI) in Nepal, which was implemented in six communities with the objective of increasing resilience to flood disasters through prevention. The project had a B/C ratio of 3.9.

Hochrainer et al. (2011) developed a BCA in four case studies related to different natural hazards. Those related to floods were:

1) The Ciliwung River in Jakarta, Indonesia, where a significant population density exists and is part of the most relevant economic areas in the country. The study consisted in assessing two typologies of houses: upper-class houses (made of masonry walls, concrete floor and tiled roof) and middle-class houses (mixed structural walls, concrete floors, galvanized sheet roofing plates). The replacement cost of the constructions in this study was US$ 19,200 and two different mitigation measures were analyzed: a) increasing flood resilience and resistance at a cost of US$ 3,100 for a typical house in the area under study and, b) increasing the height of the construction by one meter with respect to the actual level of the building, with a cost of approximately US$ 9,345. The B/C ratios are shown in Table 34.

Table 34. Summary of the B/C ratio for the mitigation measures in River Ciliwung, Indonesia

Mitigation measure	**Return period (years)**	**Masonry (upper class)**				**Combined Wall (middle class)**			
		B/C		**B/C**		**B/C**		**B/C**	
		Discount rate		**Discount rate**		**Discount rate**		**Discount rate**	
		5%	12%	5%	12%	5%	12%	5%	12%
Improvement of flood resistance	10	0.49	0.36	0.63	0.46	0.10	0.07	0.11	0.08
	25	0.90	0.50	1.16	0.64	0.18	0.10	0.21	0.11
1-meter elevation	10	0.83	0.61	1.18	0.86	2.06	1.51	3.69	2.70
	25	1.51	0.84	2.15	1.20	3.77	2.10	6.73	3.75

Source : Hochrainer et al. (2011)

2) The Rohini River in the city of Uttar Pradesh, India, has a drainage basin of at least 870 km^2. Because of its flat topography, small deviations from the natural flow of water could cause a series large-scale floods in the long term. The basin of this river is highly populated by communities living in poverty conditions. Two typical constructions in the area were analyzed, i) "*Kacha*" (a house built with clay and/or earth as main construction material) and, ii) "*Pukka*" (a house built with brick as main construction material) with replacement costs of US$ 150 and US $1,500, respectively. The following six risk mitigation measures were considered:
    - Measure 1 (Replacement within the first year): Demolish the clay/earthen house and replace it with a new one using the same construction material and adding stilts, with a total cost of US$ 175.

- Measure 2 (Replacement within the first year): Demolish the clay/earthen house and replace it with a new one using more resistant materials such as brick and adding stilts with a total cost of US$ 1,525.
- Measure 3 (Replacement within the first year): Demolish the brick house and replace it with a new one using the same construction material besides adding stilts with a total cost of US$ 1,525.
- Measure 4 (Replacement at the end of the original lifetime): Replace the clay/earthen house with the same construction material and adding stilts with a total cost of US$25.
- Measure 5 (replacement at the end of the original lifetime): Demolish the clay/earthen house and replace it with a new one using more resistant materials such as brick besides adding stilts with a total cost of US$ 1,375.
- Measure 6 (replacement at the end of the original lifetime): Replace the brick house with a new one using the same construction material and adding stilts with a total cost of US$ 25.

Table 35 summarizes the B/C ratios for some of the above-mentioned cases with different discount rates.

Table 35. Summary of the B/C ratios for some mitigation measures in the Rohini River

Mitigation measure	**Return period (years)**	**Clay/earthen – B/C**		**Brick –B/C**		**Removed clay/earthen – B/C**		**Removed brick B/C**	
		Discount rate		**Discount rate**		**Discount rate**		**Discount rate**	
		5%	12%	5%	12%	5%	12%	5%	12%
Replace with a clay/earthen building and adding a stilt	10	0.36	0.31	N/A	/N/A	2.83	2.42	N/Aa	/N/A
	25	1.42	0.8	N/Aa	N/Aa	9.94	5.6	/N/A	/N/A
Replace with a brick building and adding a stilt	10	0.05	0.04	0.04	0.04	0.06	0.05	2.8	2.4
	25	0.23	0.13	0.18	0.10	0.21	0.12	11	6.22

Source *:* Hochrainer et al. (2011)

Lickley et al. (2015) published a theoretical application for a power plant in Galveston Bay, USA. The main objective of this study was to provide tools for appropriate investments in risk mitigation and management in coastal areas. Using a probabilistic approach, the authors generated feasible events in addition to historical simulations in the domain under study. The authors also considered a risk mitigation measure, consisting of dikes with a height of

1.5 meters with a construction cost of US$1,000,000 per unit length. Table 36 summarizes some relevant data for this risk mitigation measure.

Table 36. Summary of the mitigation costs in Galveston Bay

Item	Total
Maintenance cost per kilometer of dike	US$ 8,900
Mitigation cost per kilometer of dike	US$1,000,000
Required dike distance	5 km
Interest rate	5%

Jonkman et al. (2004) made a compilation of projects associated to the applicability of the BCA in decision-making processes. The information focused mainly on flood protection strategies in the Netherlands. The analyzed cases were the following:

1) The River Dike Reinforcement Criteria Testing Commission project, developed in 1992, recommended the design of dikes able to withstand water levels associated to an annual frequency of 1/1250 (i.e. 1/return period). The objectives of this study were: i) identifying the policies that provide high security levels and at the same time are feasible from the economic perspective and, ii) preserving the natural and cultural ecosystem of the rivers that interact in the Netherlands. Table 37 shows the summary of the results, where the expected benefits after reducing the projected floods exceeded the investment costs.

Table 37. Investment costs and risk reduction estimation for the options considered by the Boertien Commission

Options	**Investment cost (US$)**	**Present value in the expected reduction for flood damage (US$)**		
		Maximum	**Medium**	**Minimum**
Security level (1/200)	327.123×10^6	0	0	0
Security level (1/500)	360.92571×10^6	3134.93×10^6	2177.55×10^6	791.64×10^6
Security level (1/1250)	408.90375×10^6	4458.69×10^6	3062.97×10^6	1083.87×10^6

* Dollar exchange date July 22, 2015 (1 EUR = US $1,09041)

Source: Jonkman et al. (2004)

2) In 2002, the *Committee Emergency Areas* was created in the Netherlands with the objective of providing technical advice in locations where the highest benefits of

implementing basins for water storage, along the Rhine and Meuse River Deltas, could exist. The main argument to justify these investments was that controlling floods is more relevant than not doing so, and therefore, investments with a value of more than EUR 1 billion were recommended. Table 38 shows the benefits after the implementation of emergency areas in a theoretical example.

3)

Table 38. Options Presented in the Committee Emergency Areas Report by Jonkman, S. N.

Alternative	Number of people to be evacuated	Flood damages (10^9 US$)	Investment costs (10^9 US$)
Current situation (no emergency zone)	500,000	59.97	0
Hypothetical situation (3 emergency zones)	35,000	0.76	1.36

* Dollar exchange date July 22, 2015 (€ 1 = US $ 1,09041)

Source*:* Brinkhuis-Jak and Kok (2004)

Leahy and Cropp (2009) studied the design of protection measures for a flood prone urban area in New Zealand. Previous studies were reviewed for the preliminary design of the risk mitigation works. The area of study corresponds to a residential-urban location and is in a low-lying area due to topographic conditions. The drainage solution was based on a network of pipes with a limited water intake and discharge capacity. In previous analyses, it was found that during a moderate flood event, certain habitable and non-habitable floor levels of a building would be flooded. However, there were no historical data available for performing any simulation at that time. Different solutions were considered for this problem such as: 1) reducing land water flow, 2) diverting the water flow upstream, and 3) increasing the water intake and the pipeline capacity. Considering these solutions, and based on economic parameters, the third option was chosen, with an estimated cost of US$ 1,500,000. The results of the BCA are shown in Table 39.

Table 39. Economic Summary of the Mitigation Measure Used: Increase Capacity of Pipelines and Water inflow

Cost of the mitigation measure (US$)	Benefits (US$)	B/C ratio
1,500,000	845,000	0.57

Hallegatte (2006) carried out a BCA six months after Hurricane Katrina in New Orleans, with the objective of updating the Category 5 hurricane flood protection systems, with an estimated cost of US$27 billion. Direct flood damages were estimated at minimum in US$20 billion, but also considering that approximately 1,000 fatalities were reported after this catastrophe and using a common valuation for the cost of a life of US$ 5 million, additional losses of US$5 billion because of the fatalities after this event were included. Besides these losses, additional US$5 billion were added to consider the numerous injuries and traumas of the affected population. In total, US$ 30 billion because of flood damages in New Orleans were calculated.

This BCA used conservative assumptions for the following variables: 1) anthropogenic environmental perturbances of the environment (e.g., climate change) and its second-order impacts, 2) the selection of a discount rate, 3) compensatory risks and secondary effects and, 4) risk aversion and heterogeneity of damages. All these aspects modified the variables of the analysis and allowed justifying the implementation of a Category 5 hurricane flood protection system. The results suggest that climate change can have a significant impact on long-term hurricane risk, where despite of the changes in population and capital at risk, it will be one of the main risk drivers in the coming decades.

Jonkman et al. (2008) performed a study in the Netherlands, where half of the country lies below sea level and on which in the absence of protection, several areas would be permanently threatened by floods coming from the sea, rivers and lakes. The Netherlands is divided into protected areas by a series of defenses, such as dikes, dunes and hydraulic structures, among others. The protected area is known as the "*dike ring*", which majority of land lies below sea level.

This study described a typical model for a common geographical area in the southwestern part of the country, using the following methodology:

- Data collection about the land use in the area of study.
- Simulation of flood patterns considering failures of the flood defense systems on a hydrodynamic model (e.g., such as the floods in the Netherlands in 1953 and Hurricane Katrina in New Orleans in 2005).

The southern areas of the Netherlands are threatened by floods because of the North Sea tides and the riverine floods in the Rhine River delta (see Figure 23). The area is protected by a flood defense system consisting of sand dunes and dikes along the rivers.

The model considered a double failure situation at Ter Heijde and The Hague, caused by high tidal waves. The simulation was carried out with the SOBEK hydrodynamic model and allowed estimating a flood area of approximately 370 km^2 (see Figure 23b). Finally, Figure23c shows the geographical distribution of the direct physical damage for that flood scenario. For this case, the total damages were estimated at approximately EUR 24 billion, which represented approximately the 6.5% of GDP for year 2000 in that country.

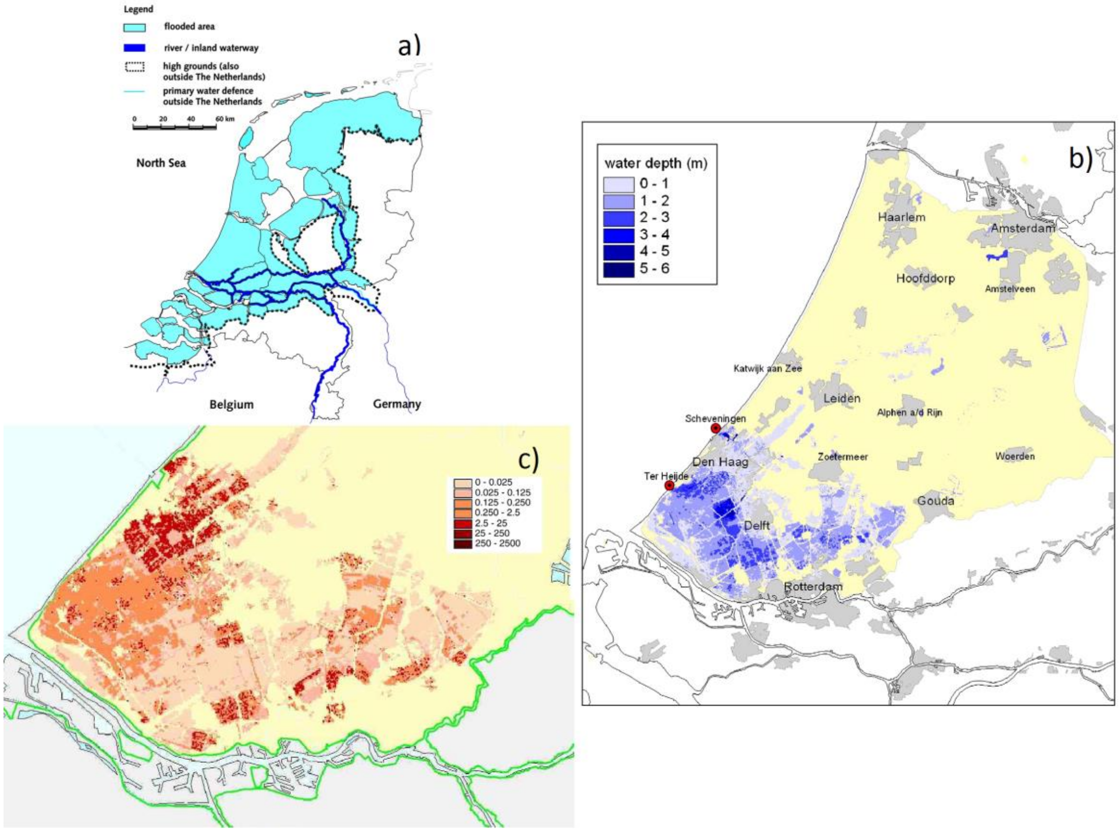


Figure 23. Flood hazard and risk assessment for the Ter Heidje and The Hague.
a) Flood- prone areas of the Netherlands b) Flood water depth because the double failure of the dikes c) Geographical distribution of direct damages in Ter Heijde and The Hague.

The following data of interest resulted from the analysis:

1. 700,000 inhabitants would be affected (corresponding to approximately 20% of the total number of inhabitants in the south area of the Netherlands).
2. Approximately 3,000 fatalities were estimated, most of which would occur in areas with high flood water depths, south of The Hague.

Although a flood scenario as the one analyzed by Jonkman et al. (2008) is highly unlikely given current protection and safety levels in the Netherlands, the probability of catastrophic floods can significantly increase due to the unpredictable variables introduced by climate change.

Shreve and Kelman (2004) published a study where comparisons of the BCA results are made for real DRR measures. The authors did not include any restrictions on the type of hazard, location, scale or any other parameter. The study highlighted that the economic costs of disasters continue to increase and the demand to demonstrate the economic benefits of DRR has also increased by policy makers. Many results that support the economic effectiveness of DRR were identified. However, key limitations were also found such as the lack of sensitivity analyses, climate change considerations, and possible damages to, or caused by, the implemented DRR measures, among others.

Table 40 shows the main parameters that were reviewed in these studies, including primary activities related to DRR, their costs, benefits and general context. Many of these studies considered structural and non-structural risk reduction measures. During the data gathering process, the difficulties to appraise certain components of non-structural activities were highlighted. Non-structural related activities often require the assessment of social and environmental aspects that do not have a market value (e.g., security perception, peace of mind and avoidance of damages to welfare). On the other hand, although direct costs are easier to estimate, the details of the structural measures such as the cost of construction materials, maintenance tasks, workforce and indirect costs and benefits, are rarely reported.

Table 40. Descriptions of DRR activities, benefits, costs and main parameters studied

Authors	Year	Beneficiaries	Scale level	Hazard (s)	Evaluated DRR activities	Benefit from DRR activities	Vulnerability: elements considered (description)	Vulnerability: elements not considered, fundamental reason	Timeframe(years)	Discount Rate (%)	B/C ratio	Structural or non-structural	Context
Holland	n.d.	Inhabitants of Navua, Fiji	Community	Flood	Early warning system	Reduction of economic losses, and injuries Reduction of the required assistance from government and other sources.	Economic losses from household level (structures, premises, possessions), business losses, government and NGO payments, charities, other losses (trauma/medical)	Humanitarian aid, trauma and irreparable articles, days lost by children due to water scarcity	20	3, 7 ,10	1.7	Non-structural	Impact assessment in all sectors and over the distributional aspects
EWASE	n.d.	Communities in flood prone areas of Austria	Community	Flood	Effectiveness of early warning systems in small basins with short hydrological response times	An increase in warning time can provide valuable time for the completion of preventive measures, however a false alarm would	Early warning system (investment costs, maintenance, physical	Does not include intangible damages. These were addresse	20	3	(Early warning system) 2.6-9.0	Non-structural	Evaluation of the possible economic benefits of an early warning system / weather service vs

						have economic costs	assets and operating costs)	d separately in a multi-criteria assessment					cost of the early warning system/weather service
Holub, et al.	2008	Local infrastructure in the Austrian Alps	Community	Flood	Local structural measures	Prevention of damage to buildings and infrastructure	Potential damage to buildings due to flash floods; cost of local structural measures	Downstream benefits; contents	80	3.5 (interest rate)	2.1-6.7	Structural	Comparative analysis of risk mitigation studies
French, et al.	2017	Residents of Piura, Peru in flood prone areas	Community	Flood	Polder construction	The elevation of existing dikes and the construction of polders reduces the flood risk	Private sector: damaged or destroyed housing; education and health, water and sanitation, agriculture, industry, commerce, and service sectors. Destroyed or damaged	Damages and benefits related to the environment (no data available)	30	12	2.2-3.8	Structural	Projection to the past

							assets (buildings, machinery, roads, etc.)						
	2017	Residents in Semarang, Indonesia, in flood prone areas	Community	Flood	Return to an integrated water and flood management protection scheme (for instance, reduction of soil subsidence by decreasing groundwater extraction), improvement of drainage systems to mitigate flood caused by tides	Flood reduction	Construction and operation costs of the structural risk mitigation measures	Social benefits are not accounted for	54 (2005-2059)	12	1.9-2.5	Structural	Projection to the past
Burton and Venton		Residents of the Philippines in hazard prone areas where DRR programs are implemented	Community	Flood	BCA of the Integrated Program for Disaster Preparedness (ICBDP) against disaster response operations undertaken by the Philippine National Red Cross	The protection of assets, such as housing, crops and livestock; health benefits, such as access to drinking water and social benefits such as safe access of children to their schools	Cost of construction of structural measures (jetties, coastal defense walls and dikes)	The authors warn that they have limited data, so they only observed the BCA and some small-scale risk	15	Not specified	24 (jetties); 4.9 (coastal defense walls); 0.7 (dikes)	Structural	Projection to the past

								mitigation projects in the CBDRM program					
White and Rorick	2010	Residents in flood prone areas of Nepal participating in the DRR program	Community	Flood	Multi-sectors, based on a combination of capacity building, early warning systems, bioengineering for riverbank protection, river bank plantations, evacuation routes, boats, embankment works and community planning	Reduction of the number of flooded houses, reduction of grains lost in storage buildings, avoidance of content losses in flooded homes, percentage of land lost due to erosion, loss of infrastructure remained the same, decrease of the number of people exposed to contaminated water sources	Damage to flooded houses and contents, loss in grain storage buildings and annual loss for crops, loss of soil due to erosion, infrastructure losses, number of exposed people to contaminated	Qualitative social and environmental benefits were not monetized	10	10	3.49	Structural and non-structural	Projection to the past

							water sources						
Heidari, A.	2013	Residents on the plains of the Dez and Karun Rivers in Iran	Community	Flood	Structural risk mitigation measures including dikes, land banks, retention dams and flood diversion	Avoided or reduced flood damage	Construction costs	Social and environmental costs (beyond the scope of the project)	25	10	0.29-1.03 land banks, 0.7-1.34 dams, 1.1 flood diversion	Structural	Projections to the past and to the future
Khan	2015	Residents of a flood prone area in Lai Basin, Pakistan	Community	Flood	1) Channel; River improvements 2) Early warning system 3) Relocation of houses along the flood plain and restoration of the wetland area.	(1) Channels which are more resistant to flooding; reduction of the maximum river flow and higher flow capacity due to river improvements; (2) decreased risk of injuries and fatalities, reduction of property damage if residents have enough time to take preventive measures; (3) risk reduction or avoidance of existing homes in the flood plain because of, improvements after restoration	(Vulnerability), using risk and damage data of the 2001 flood and triangulation of property costs made with real estate agents in the flood plain; data from various regional and global studies of the region (damage vs. water depth)	The social benefits of flood prevention (for instance, the reduction of the burden of disease, trauma, disruption of livelihoods) are not included because there	30	12	8.55-9.25, channel, river improvement; 0.96, early warning system; 1.34, relocation of houses and restoration of the wetland area	Structural and non-structural	Projection to the past

							corroborated with anecdotal evidence and qualitative surveys of the area; (economic effects) malaria and other reported diseases.	were no reliable data					
Kull	2008	Residents in a flood prone area in the Gangetic Basin (Nepal and India)	Community	Flood	At individual level (raising the steps of the houses and forage storage units, rainwater harvesting, raising of hand pumps and toilets). At community level (early warning system, raising the community's manual pumps and toilets, the construction of flood shelters, the establishment of grain and seed storages/banks, maintenance of drainage (mainly	Reduction of the risk of death, injury or illness related to floods. Improvements to agricultural practices and productivity	Data were gathered through surveys on specific disaster losses, overcoming, exposure, vulnerability, preference and B/C data. Cost of the 2003 embankment project	Authors point out that, although the conclusions seem sound, the data availability and quality limit the analysis.	43 (2007-2050)	0-20	2-2.5	Structural and non-structural	Projection to the past (Nepal) and to the future

					at bottlenecks), development of self-assistance groups and the purchase of boats for the community). At societal level (promotion of agriculture adapted to floods and strengthening of the health system).								
IFRC	2017	Residents in flood prone communities in Bangladesh	Community	Flood	Creation of community groups to raise risk awareness and have better preparedness, the construction of evacuation routes, establishment of emergency funds for community disasters, construction of piped wells to increase access to drinking water; sensitize and training in health and sanitation	Community risk awareness groups, as well as knowledge about health and sanitation. Evacuation routes reduce fatalities and injuries; the emergency fund allows reconstruction and recovery processes after a disaster.	Household surveys and reports were used to estimate the costs and benefits of the RRD program	Improvement of community fabric, higher security sense, lives saved, avoided injuries; hybrid vegetable seeds (future benefits), etc.	15	7.74	1.18-3.04 future protection benefits (3.05-4.90)	Structural and non-structural	BCA was performed to evaluate the economic efficiency of the DRR programs

Kunreuther, et al.	2013	Residents in the 34 countries most prone to flood damages	National	Flood	Construction of a high 1m height wall to protect homes in the 34 most flood prone communities worldwide	An investment of US$904 billion in the construction of protection walls around houses or US$5.2 trillion to elevate existing houses in 34 of the countries most affected by floods. 61,000 lives in the next 50 years could be saved	Reduction of damages to infrastructure and property and prevented fatalities	Other social and environmental benefits (beyond the scope of the study)	10, 25, 50	5, 12	60 constructions of the 1m wall; 14.5 for house elevation	Structural	Projection to the future
Venton and Venton	2004	Residents of two flood and drought prone communities where DRR activities have been implemented	Community	Flood and droughts	Two communities with existing DRR programs selected to assess the benefit of these programs; its impacts were analyzed in five dimensions (natural, physical. human, social and economic)	(Bihar) planting trees to increase soil stability; creation of a development fund capable of providing loans for reconstruction; (Khammam) elevation of manual water pumps to guarantee the supply of drinking water; reduction of damages and losses to people due to effective evacuation, reduction of health problems, and ensuring that there will be no blockage once the waters recede;	(Bihar) installation of manual pumps, boats, motorcycles for personnel transport, construction of evacuation routes, community training, support personnel expenses (office rental, travel/accommodation, communication),	The following aspects were not considered due to lack of data: destruction of crops soil after severe floods /droughts; destroyed houses by floods; health	20s (Bihar); 15 (Khammam)	10	Bihar (baseline scenario 3.17-4.88); Khammam (baseline scenario 3.7-20.05)	Non-structural	Projection to the past

							personnel expenses (personnel of projects and consulting)	costs due to flood/drought; social relations costs; health of the survivors					

Source: Shreve and Kelman, 2014

5 PARAMETRIC MODEL FOR DISASTER RISK MITIGATION

5.1 INTRODUCTION

In the previous chapter, an approximation of the consequences of implementing a risk mitigation measure, quantified in terms of the LEC and its associated AAL reduction was introduced. It was identified that this analysis requires a much more comprehensive study. The variants that also exist in the wide spectrum of risk mitigation measures for different natural hazards were reviewed and discussed.

It is worth highlighting that to assess the usefulness of a specific risk mitigation measure appropriately, an estimation of the LEC that reflects future possible losses after its implementation is needed. In many developing countries, this information is practically non-existent, and acknowledging this limitation is a key step to yielding robust results. In addition, the range of possible risk mitigation measures is broad, since they can influence the type of structure, the natural hazard or both. In this context, this chapter proposes a model that seeks to conglomerate various types of structures into a generic model for a representative hazard, so that the effects of implementing a risk mitigation measure can be quantified through a new LEC, which - as explained in Chapter 3 - allows to see the risk variation between initial and mitigated risks.

Recalling the concept introduced in Chapter 4, implementing a risk mitigation measure modifies the vulnerability function of an exposed asset. For instance, any changes and improvements in the structural system, modify the expected behavior of that asset when subjected to hazard intensities that can cause losses. This change in the vulnerability component is also reflected in a change in the LEC that can be understood in two different ways: 1) as a lower loss for the same exceedance rate or, 2) as a lower exceedance rate for the same loss value.

Because of the variability and low frequency of catastrophic events, this study proposes a simplified model that estimates key parameters that are relevant for the physical vulnerability of infrastructure. The originality of this model lies in its ability to explain the effects of implementing a risk mitigation measure after modifying these parameters. This study focuses on two hazards: earthquakes and floods.

In the case of earthquakes, the parameters will be related to the hazard zone characteristics, such as geographical location, the distance to active faults and other well-known factors that affect the occurrence of earthquakes and the behavior of typical structures (e.g., soil type, structural system, construction material and incidence degree of the mitigation measure).

The definition of hazard zones makes the model more realistic since the protection level that a risk mitigation measure can provide, inevitably depends on the characteristics of the area where exposed assets are located and on their construction types. For example, it is not the same to retrofit a new building in an area with low seismic hazard than to do so in a place with a higher incidence of earthquakes; or to retrofit an old building that has already been affected by previous events. Thus, the implementation of a parametric mitigation model with these characteristics gives the decision-maker an approximation - but robust idea - of what could happen in the country under study in spite of uncertainties such as construction type and soil conditions in the area of interest.

This model also has as advantage that it gives the decision-maker the possibility to assess hypothetical scenarios of interest. For instance, by changing the mitigation level (low, medium or high) and comparing the consequences of the choices under different scenarios.

The mandatory components to build a parametric model, such as the one defined above, are explained in detail next. The results of this model are based on the outcomes of probabilistic risk assessments, whose main objective is to determine the frequency of losses that can occur in the exposed assets, (i.e. infrastructure) because of the occurrence of natural hazards, by quantifying and propagating the existing uncertainties throughout the process. Thus, the essential components for any probabilistic earthquake risk assessment are the following:

1. Earthquake hazard analysis
2. Definition of the inventory of exposed assets
3. Development of vulnerability models for the exposed assets

5.2 HAZARD ANALYSIS (EARTHQUAKE)

The seismic hazard analysis in this case is based on the estimation of exceedance rates for different acceleration values, which indicate the average number of times that a given acceleration level is exceeded within a predefined timeframe. The intensity exceedance rate is defined by expression (5-1) and is schematically shown in Figure 24.

$$\lambda(a) = K * \left(\frac{a_0}{a}\right)^r, \ a > a_0 \qquad (5\text{-}1)$$

where: *a* indicates the soil acceleration, a_0 is the threshold acceleration level which depends on the characteristics of the area under study and $K = \lambda(a_0)$ is the exceedance rate of the chosen threshold acceleration level. This parameter is also an indicator of the hazard level in the area of study, meaning that for the same value of a_0 a higher *K* value will be obtained in areas with high earthquake hazard, Finally, *r* represents how fast, for large acceleration values, the exceedance rate decays.

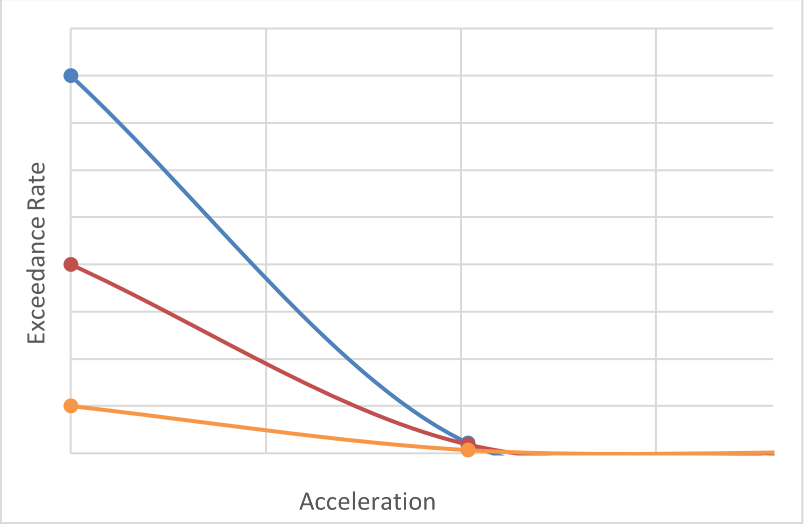


Figure 24. *λ*(*a*) functions for different parameters

If acceleration is assumed to be a random variable, its exceedance rate $\lambda(a)$ can be obtained with the following expression:

$$\lambda(a) = K * Probability(Acceleration > a) = \quad (5\text{-}2)$$

$$K * [1 - Probability(Acceleration \leq a)] = K * [1 - F_A(a)] \quad (5\text{-}3)$$

The cumulative probability function, $F_X(x)$, of any random variable *x* can be related its probability density function $f_X(x)$ as:

$$f_X(x) = \frac{d}{dx} F_X(x) \quad (5\text{-}4)$$

A result that allows to calculate the occurrence probability density function for any given acceleration level.

$$f_A(a) = \frac{d}{da} F_A(a) = \frac{d}{da}\left[1 - \frac{\lambda(a)}{K}\right] = -\frac{1}{K}\frac{d}{da}\lambda(a) \quad (5\text{-}5)$$

$\lambda(a)$ can therefore be rewritten as:

$$\lambda(a) = K * {a_0}^r * a^{-r} \tag{5-6}$$

So:

$$\frac{d}{da}\lambda(a) = K * {a_0}^r * (-r) * a^{-r-1} \tag{5-7}$$

Which makes:

$$f_A(a) = r * {a_0}^r * \left(\frac{1}{a}\right)^{r+1} \tag{5-8}$$

5.3 PHYSICAL VULNERABILITY OF INFRASTRUCTURE

This concept refers to the damage that hazard intensities (e.g. ground acceleration, water depth, wind speed) would cause on a given asset. Physical vulnerability is usually quantified in terms of an average loss percentage, or as the required monetary value to repair the affected asset to the same conditions it had before the occurrence of an event. Physical vulnerability, in this context, is represented in terms of the so-called “vulnerability functions”. A vulnerability function provides a relationship between the loss distribution and the hazard intensities that can be produced by a specific event.

In the context of disasters, a relationship between a variable associated to nature and how it affects the exposed assets is required. In this study, the expected loss that a structure could have, conditional to a hazard intensity level (e.g., soil acceleration in the case of earthquakes) is calculated as:

$$L(a) = 1 - e^{(-\ln 2)*\left(\frac{a}{\bar{a}}\right)^{\rho}} = 1 - 0.5^{\left(\frac{a}{\bar{a}}\right)^{\rho}} \tag{5-9}$$

Where:

a corresponds to the ground acceleration,

$\bar{a}$ is the acceleration level that causes an expected loss of 50%, and,

ρ is a parameter defining the curvature of the vulnerability function. In structural engineering terms, this last parameter defines how fast the structural system under analysis presents losses given a hazard intensity measure.

$L(a)$ is the expected loss conditional to an acceleration level, $E(Loss|Acceleration)$.

$$E(Loss|Acceleration)=E(L_i|A) \tag{5-10}$$

The expected loss can be related to its variance in the following way:

$$\sigma_{P_i}^2(L_i|A) = Q * [E(L_i|A)]^{r-1} * [1 - E(L_i|A)]^{s-1} \tag{5-11}$$

where:

$$Q = \frac{V_{max}}{D_0^{r-1}(1-D_0)^{s-1}} \tag{5-12}$$

and,

$$s = \frac{r-1}{D_0} - r + 2 \tag{5-13}$$

V_{max} is the maximum variance, D_0 is the damage level for which this maximum variance occurs and *r* is set equal to three. All these parameters depend on the structure type.

According to expert criteria, the following values for *r* and D_0 are used herein:

$r = 3$

$D_0 = 0.5$

After using these values, the variance and standard deviation of the loss, L_i, can be defined with the following formulas:

$$\sigma_{L_i}^2(L_i|A) = 16 * V_{max} * [E(L_i|A)]^2 * [1 - E(L_i|A)]^2 \tag{5-14}$$

$$\sigma_{L_i}(L_i|A) = 4 * [E(L_i|A)] * [1 - E(L_i|A)] * \sqrt{V_{max}} \tag{5-15}$$

The expected value and standard deviation of the losses for a particular building typology, when analyzed jointly, represent a vulnerability function, as shown in Figure 25.

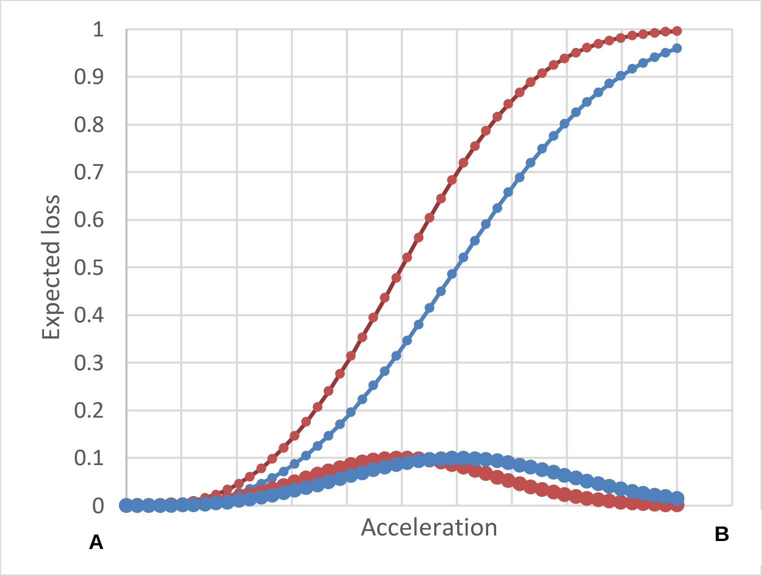


Figure 25. Vulnerability functions for different parameters

It is assumed that losses[12] conditioned to an acceleration value follow a Beta distribution, whose parameters are *a* and *b*. Therefore, its probability density function is:

$$Probability(L = l_i|A) = f_{L_{i|A}}(L_i = l_i|A) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} {l_i}^{a-1}(1-l_i)^{b-1} \qquad 0 \le l_1 \le 1 \tag{5-16}$$

Although the expected loss can be obtained from the acceleration, it can also be obtained using *a* and *b* values in the following way:

$$E(L_i|A) = \frac{a}{a+b} \tag{5-17}$$

The same applies for the estimation of the variance.

$$Var(L_i|A) = \frac{ab}{(a+b)^2(a+b+1)} \tag{5-18}$$

Economic losses, as a function of the hazard intensities, can be assessed with these data. *a* and *b* parameters can be estimated as:

$$a = \left[\left(\frac{1-E(L_i|A)}{Var(L_i|A)} - \frac{1}{E(L_i|A)}\right) * E(L_i|A)^2\right] \tag{5-19}$$

$$b = \frac{a}{E(L|A)}\left(1 - E(L_i|A)\right) \tag{5-20}$$

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[12] As a percentage with respect to the replacement cost of the infrastructure

These parameters are needed to calculate both, the loss exceedance rates (i.e. LEC) and the AAL for any hazard level and characteristics of the structures (i.e. construction material, type of retrofitting or mitigation measure implemented).

5.4 RISK METRICS OF THE PARAMETRIC MODEL

The LEC - one of the most important outputs of a probabilistic risk assessment - gives the relationship between a given loss value, L_i, and its annual exceedance rate, after estimating losses associated to a catalogue of stochastic events that includes all feasible manifestations of the hazard(s) of interest.

As mentioned in Chapter 3, there is a relationship between the exceedance rates and exceedance probabilities. That is, from the LEC, an exceedance probability (EP) curve, for any timeframe (e.g., 1, 20, 50 years), can be obtained, and vice versa. The EP curve is the graphical representation of points defined as: $[l_i, \Pr(L_i > l_i)]$. This curve has all the needed information to characterize the way in which losses would occur; however, there are situations where using the complete curve is not practical and it is more convenient to use specific metrics to express risk as an integer.

In this study, soil acceleration is used in the earthquake analysis as the intensity measure that better correlates with losses. This means that losses are conditional to the occurrence of an event and then the total probability theorem becomes useful.

By adapting this theorem to the available information, the exceedance probability of any loss level, l_i, can be obtained as:

$$\Pr(L_i > l_i) = \int_a \Pr(L_i > l_i | Acceleration = a) * \Pr(Acceleration = a)\, da \tag{5-21}$$

$$\Pr(L_i > l_i) = \int_a \Pr(L_i > l_i | Acceleration = a) * f_A(a) da \tag{5-22}$$

$$\Pr(L_i > l_i) = \int_a \Pr(L_i > l_i | Acceleration = a) * r * {a_0}^r * \left(\frac{1}{a}\right)^{r+1} da \tag{5-23}$$

By having an empirical way to obtain exceedance probabilities for any loss level, loss exceedance rates can be obtained by multiplying this value by the number of recorded events of interest.

$$v(l) = K * \Pr(L_i > l_i) = K * \int_a \Pr(L_i > l_i | Acceleration = a) * r * {a_0}^r * \left(\frac{1}{a}\right)^{r+1} da \tag{5-24}$$

As it explained in Chapter 3, the AAL can be obtained by integrating the LEC:

$$AAL[13] = \int_{l=0}^{l=exposed\ value} v(l)dp = N \int_{l_i=0}^{l_i=exposed\ value} \mathrm{Pr}(L_i > l_i)\mathrm{dp_i} \qquad (5\text{-}25)$$

Or by means of the following probability result:

$$E(X) = E_Y(X|Y) \qquad (5\text{-}26)$$

By considering both, hazard and vulnerability associated to the exposed assets, the AAL in this study takes the following form:

$$AAL = number\ of\ events * E(L_i) \qquad (5\text{-}27)$$

$$AAL = K * \ E_A(P_i|A) \qquad (5\text{-}28)$$

$$AAL = K * \ \int_a \ L(a) * f_A(a)\, da \qquad (5\text{-}29)$$

$$AAL = K * \int_a \ \left[1 - .5^{\left(\frac{a}{\bar{a}}\right)^{\rho}}\right] * \ r * {a_0}^r * \left(\frac{1}{a}\right)^{r+1} \ da \qquad (5\text{-}30)$$

5.5 ESTIMATION OF THE PARAMETERS

Representing hazard and physical vulnerability of the exposed assets in the ways described before, allows to propose a model based on four parameters: a_0, r, ρ and $\bar{a}$.

Considering the formulas in the previous section, the first parameter represents the exceedance rate of the acceleration and the second one corresponds to the expected damage that the exposed asset will have associated to a given acceleration level.

$$\lambda(a) = K * \left(\frac{a_0}{a}\right)^r, \ \ a > a_0 \qquad (5\text{-}31)$$

$$L(a) = 1 - \ e^{(-\ln 2)*\left(\frac{a}{\bar{a}}\right)^L} = 1 - .5^{\left(\frac{a}{\bar{a}}\right)^L} \qquad (5\text{-}32)$$

parameter *K* is the result of selecting $a_0\ and\ r$[14]

---

[13] In this case N = k

[14] $K = \lambda(a_0)$

Since $\lambda(a)$ defines the exceedance rate of the soil acceleration, it intrinsically defines the hazard to which a region or country is exposed to, due to its geographical characteristics. Therefore, its parameters cannot be modified after implementing a risk mitigation measure.

The formulation of $\lambda(a)$ has the following property, which is useful for estimating the parameters:

$$\log[\lambda(a)] = \log\left[K * \left(\frac{a_0}{a}\right)^r\right] \tag{5-33}$$

$$\log[\lambda(a)] = \log(K) + log\left[\left(\frac{a_0}{a}\right)^r\right] \tag{5-34}$$

$$\log[\lambda(a)] = \log(K) + r * [\log(a_0) - \log\,(a)] \tag{5-35}$$

$$\log[\lambda(a)] = [\log(K) + r * \log\,(a_0)] - r * \log\,(a) \tag{5-36}$$

The last equation can be adapted to a straight line if the variables are renamed in the following way:

$$y = \log[\lambda(a)] \tag{5-37}$$

$$\beta_0 = \log(K) + r * \log(a_0) \tag{5-38}$$

$$x = \log(a) \tag{5-39}$$

$$\beta_1 = -r \tag{5-40}$$

$$y = \beta_0 + \beta_1 * x \tag{5-41}$$

With this approach, a regression can be performed to obtain the line that fits best $\log[\lambda(a)]$. It is important to mention that this procedure can be used if data on the intensity (e.g., acceleration or water depth) exceedance rates at a given location are available. Obtaining detailed information with accurate values for a given location, requires a considerable amount of time and resources.

When the values of a_0, r and K, are known, the next step is to find the parameters l and $\bar{a}$ that estimate, in the best possible way, the expected losses for different hazard intensity levels (e.g., acceleration in the case of earthquakes). To be able to compare the initial and mitigated states, parameters l and $\bar{a}$ in its initial state must be estimated first.

Since the objective is to compare the LEC of the initial and mitigated risks, the best estimate of l and $\bar{a}$ is the one that better reproduces the exceedance rate reported by a decision-maker.

From the parameters that represent the initial hazard level and vulnerability conditions of the exposed assets, it is necessary to estimate the ones for the mitigated state. Since $a_0, r \text{ and } K$ are only related to hazard, there will be no changes on them when implementing a risk mitigation measure. From $\rho \text{ and } \bar{a}$ parameters, the one that will change after implementing a mitigation measure is $\bar{a}$. This change consists in an increase of $\bar{a}$, meaning that in the mitigated state, an expected loss of 50% will occur at a higher hazard intensity level. However, this behavior will also occur at other hazard intensity levels because of the functional form of $L(a)$ and therefore, the overall variation has consequences in the previously mentioned risk metrics.

Again, the formulas for estimating the AAL and the loss exceedance rate are:

$$AAL = K * \int_a \left[1 - .5^{\left(\frac{a}{\bar{a}}\right)^{\rho}}\right] * r * {a_0}^r * \left(\frac{1}{a}\right)^{r+1} da \tag{5-43}$$

$$v(l) = K * \Pr(L_i > l_i) = K * \int_a \Pr(L_i > l_i | Acceleration = a) * r * {a_0}^r * \left(\frac{1}{a}\right)^{r+1} da \tag{5-44}$$

Displacing $\bar{a}$ to the right will result in a lower AAL and in a smaller variance of losses. The effect of these changes will also modify the values of the *a* and *b* parameters, which are used to estimate the loss exceedance probabilities associated to a given acceleration value. This in turn means that the exceedance rate, $v(l)$, will be modified, but not necessarily in the same proportion throughout all its values. This study will denote the exceedance rate that accounts for the risk mitigation measure as $v_m(l)$.

With the LECs for the initial and mitigated states, some factors that reflect the weight of the second case with respect to the first one can be estimated as:

$$factor_i = \frac{mitigated\ exceedance\ rate\ of\ loss\ i}{exceedance\ rate\ of\ loss\ i} \tag{5-45}$$

If the available LEC to the decision-maker is defined by "*n*" points (i.e. loss values), there will be "*n*" factors, to be grouped into a vector as follows:

$$\overline{V_{TS}} = \begin{pmatrix} factor_1 \\ factor_2 \\ factor_3 \\ \vdots \\ factor_n \end{pmatrix} \tag{5-46}$$

where *TS* is the type of structure and *m* are the building typologies and therefore, there will be as many vectors as building typologies, for high, medium and low levels of risk mitigation measures.

The conceptual development presented in this study assumes that the countries in which this methodology will be applied have detailed information on probabilistic risk assessments (for the earthquakes analysis) that considers the initial and mitigated states (as per the implemented risk mitigation measures by the decision-maker) of the exposed infrastructure. It is known by now that the countries where the methodology will be applied do not count with sufficient data. In order to help decision-makers preparing a robust analysis, this study proposes generic mitigation vectors for earthquakes and floods, which the natural hazards that recurrently affect Latin American countries. The generic mitigation vectors presented in this study provide a robust solution to the lack of risk assessments that consider mitigation measures on the exposed infrastructure that were identified in the literature review. The proposed vectors, together with the associated costs of the risk mitigation measures they represent, are included in Annex 1.

5.6 SUMMARY OF THE PARAMETRIC MODEL

The comparison between the initial and mitigated states of the infrastructure considered in this model was performed using parameters that reflect their physical vulnerability in both states. The use of a parametric model helps represent the two hazards in a region where information on hazard or vulnerability of the exposed assets is insufficient, due to the complexity and time-consuming nature of the task.

The parameters for the initial state are estimated from information about the natural phenomena that causes losses and from the LEC. In cases where no detailed data about the hazard exists, the parameters of a location with similar characteristics can be used. For all components related to a hazard, the parameters representing the mitigated state will be the same as those of the initial one. However, for those related to the physical vulnerability of the assets there will be modifications. With these two sets of parameters, the AAL and the LEC for the two states can be compared and the benefits of having implemented a risk mitigation measure can be estimated.

Finally, in countries where there is no detailed information for estimating the parameters of the initial state, and their changes when implementing a mitigation measure, the model allows to use information from other locations with similar characteristics to modify the LEC using a vector with different weights assigned to particular loss levels.

5.7 ESTIMATION OF A RISK MITIGATION MEASURE SUBJECT TO A BUDGETARY RESTRICTION

This methodology proposes a three-level risk mitigation measure (low, medium, and high). Each of them has different costs and impacts on the risk structure of the country under study. The implementation of these measures will result in a displacement of the LEC (with respect to the one representing the initial state), which is to be understood as a decrease in the exceedance rates for most loss values.

The estimation of risk reduction after implementing a mitigation measure is based on a set of values called mitigation vectors. Each of these values is a number between 0 and 1 that represents the remaining risk (as a percentage) at each loss level in the LEC, and as a function of the exposed value share it represents in an economy. In this way, depending on the share that each loss represents with respect to the total exposed value, its exceedance rate reduction value can be assigned.

In this study only three levels for the risk mitigation measures have been considered and for which the reduction of loss exceedance rates are known. However, a procedure was developed for a LEC approximation derived with different implementation costs than the ones previously used (for the low, medium and high mitigation levels) as a function of the amount of loss with respect to the total exposed value.

A larger mitigation cost is reflected in a LEC that lies closer to the origin, as shown in Figure 26, or in the form of a lower PML plot, as shown in Figure 27.

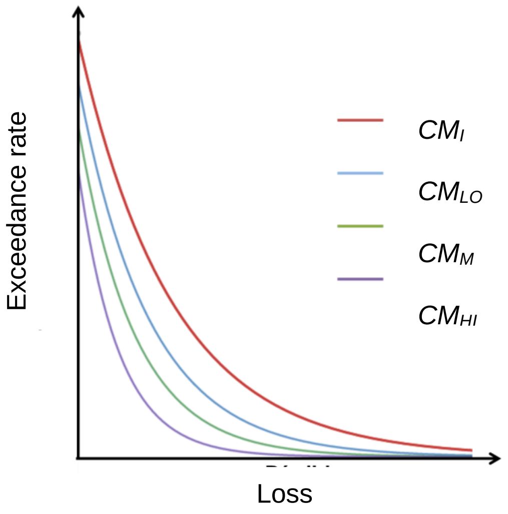

Figure 26. LEC for different risk mitigation measures

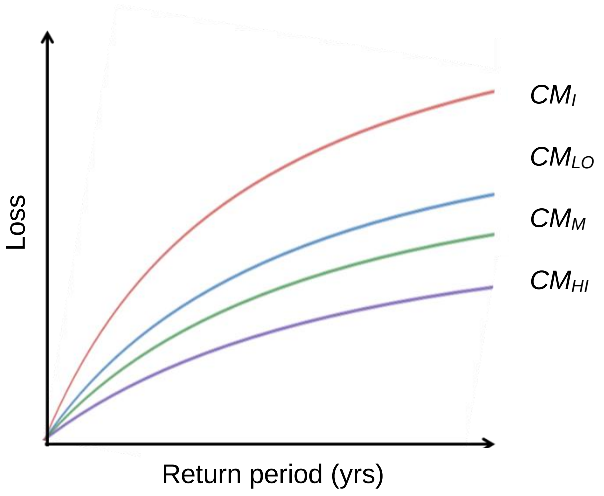

Figure 27. PML plots for different risk mitigation measures

This procedure starts by locating the cost (or allocated budget) for implementing a risk mitigation measure, denoted herein as *MB*, within the estimated values in the initial methodology for the country under analysis. Considering the values in Table 41, for any value of *MB* there will be a lower and a higher mitigation cost, denoted as MB_j and MB_{j+1}, respectively.

Table 41 Cost for the mitigation options

Cost of mitigation measure		
	Formula[15]	**Variable**
Initial state (Initial LEC)	0% of the exposed value	$MB_0 = \$0$
Low mitigation	1% of the exposed value	MB_{LO}
Medium mitigation	5% of the exposed value	MB_M
High mitigation	40% of the exposed value	MB_{HI}

---

[15] The proposal of the formula based on the exposed value is the same regardless of the country. However, the associated cost will be determined by the value of the infrastructure at each country.

Each of these costs is associated to a different LEC, obtained from the previously described mitigation vectors. This means that for any loss level, $\bar{L}$, the exceedance rates can be obtained from the LECs of MC_j and MC_{j+1}. This process is schematically shown in Figure 28.

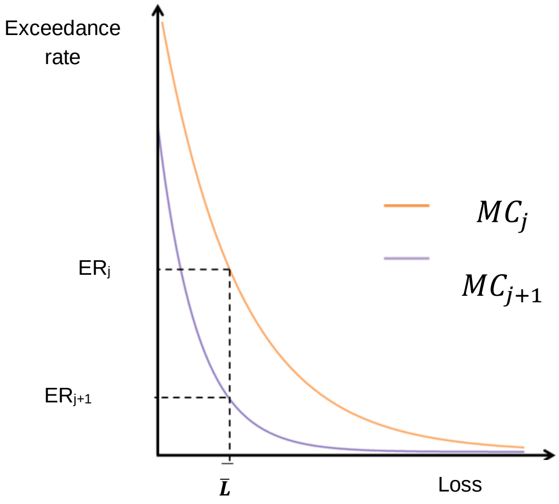

Figure 28. LEC for different risk mitigation costs

Since this procedure is valid for each fixed loss value, $\bar{L}$, that is within the covered loss range by the LEC, it is possible to define the pairs (MC_j,ER_j) and (MC_{j+1},ER_{j+1}) and with them, estimate a new exceedance rate for $\bar{L}$ based on the previously determined value for *MB*. This approach is schematically shown in Figure 29.

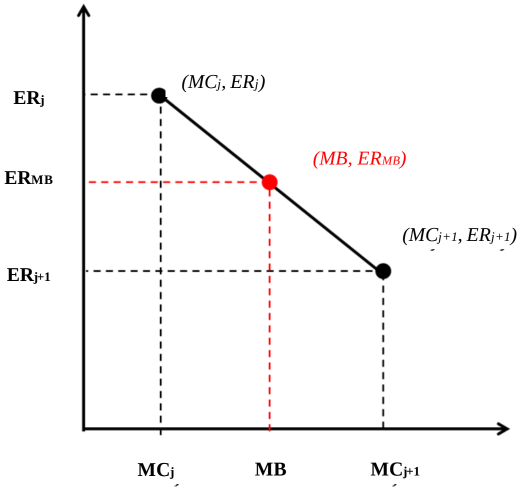

Figure 29 Estimation of the loss exceedance rate corresponding to a budgetary constraint

The value of interest in Figure 29 is ER_{MB}. For its estimation, a linear interpolation process can be performed after assuming that two points with known coordinates (in this case (MC_j,ER_j) and (MC_{j+1},ER_{j+1})), are part of the same straight line, and that the value to be estimated is somewhere between them. The detailed description of the process is the following:

1. Estimate the slope between points (MC_j,ER_j) and (MC_{j+1},ER_{j+1})

Since the values for these four variables are known, the slope can be calculated as:

$$m = \frac{\Delta ER}{\Delta MC} = \frac{ER_j - ER_{j+1}}{MC_j - MC_{j+1}} \tag{5-47}$$

2. Calculate the ordinate to origin

The straight line that we are estimating has the form $ER = (m * MC) + b$. After isolating *b*, the following expression is obtained:

$$b = ER - (m * MC) \tag{5-48}$$

The *m* value is substituted by the value obtained in step 1, ER by ER_j and MC by MC_j[16]

3. Knowing these two values it is possible to estimate ER_{MB} as:

$$ER_{MB} = (m * MB) + b \tag{5-49}$$

4. The procedure is repeated for all values of $\bar{L}$ in the LEC, resulting in a new curve based on a defined cost or allocated budget.

Table 42 shows the costs of different levels for risk mitigation measures, using representative values for Honduras.

Table 41. Illustrative example of risk mitigation costs at country level (example of Honduras)

Mitigation costs for Honduras		
	Formula	**Cost (US$ million)**
Initial State (Initial LEC)	0% of exposed value	0.0
Low Mitigation	1% of exposed value	77.87
Medium Mitigation	5% of exposed value	389.35
High Mitigation	40% of exposed value	3,114.80

---

[16] The result of the ordinate to the origin (*b*) is the same if instead of using the values of (ER_j,MC_j) the values for (ER_{j+1},MC_{j+1}) are used.

ANNEX 1: Risk mitigation proxy

Introduction

The implementation of structural risk mitigation measures for disaster risk reduction (DRR) seeks to reduce the probable future losses caused by natural events. In the context of decision-making processes related to public investment in disaster risk mitigation, the risk to which a specific area is exposed to, as well as the risk reduction obtained after the implementation of a measure, is usually represented through a LEC (see Figure 30). A LEC relates different loss values (on the exposed infrastructure) to their exceedance rates (usually in an annual basis), caused by one or more hazards.

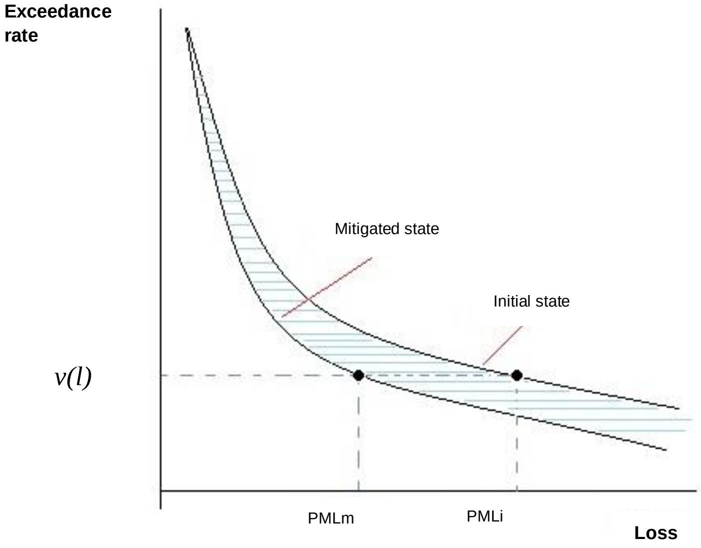

Figure 30. LEC for the initial and mitigated states

Having risk results in terms of the probabilistic metrics shown in Figure 30 is the first step for an appropriate decision-making process. Therefore, this type of risk assessments should be developed to obtain precise information on current risk levels of different countries as well as on the benefits of implementing specific risk mitigation measures in them.

The Inter-American Development Bank (IADB) has developed country risk profiles that estimate probabilistic losses caused by feasible hazard events, which could affect countries in Latin American and the Caribbean. Full details can be found in: https://publications.iadb.org/en.

These country risk profiles reflect the *initial state* of the analyzed infrastructure. Studies for that same infrastructure that consider the *mitigated state* are still required (see Figure 30) and this is an objective expected to be achieved in the coming years.

The methodology presented in this study allows all users to feed the model with the highest available level of detail. The user (e.g., decision-maker, analyst or modeler) must have the necessary risk assessments (initial and mitigated states) to use the methodology presented herein. If the minimum necessary risk mitigation information to feed the model is not available, the user has the option of using a generic proxy for risk mitigation measures, which has been specially developed for the application of this methodology. The objective of this proxy is not to replace or avoid the development of detailed analyses, but to provide the user with a robust proposal that allows for the application of the methodology described herein in the absence of essential information for decision-making processes. This alternative approach does not provide a detailed risk mitigation assessment, which should be developed by countries that are interested in obtaining results with a lower uncertainty range.

Background

The country risk profiles developed by the IADB that account for the initial state of the analyzed infrastructure, were developed making use of multi-hazard probabilistic risk assessment approaches. Any probabilistic risk assessment should include, at least, the following components (See Figure 31):

- Analysis of the natural hazards.
- Identification and characterization of the exposed infrastructure.
- Vulnerability analysis.
- Probabilistic risk assessment.

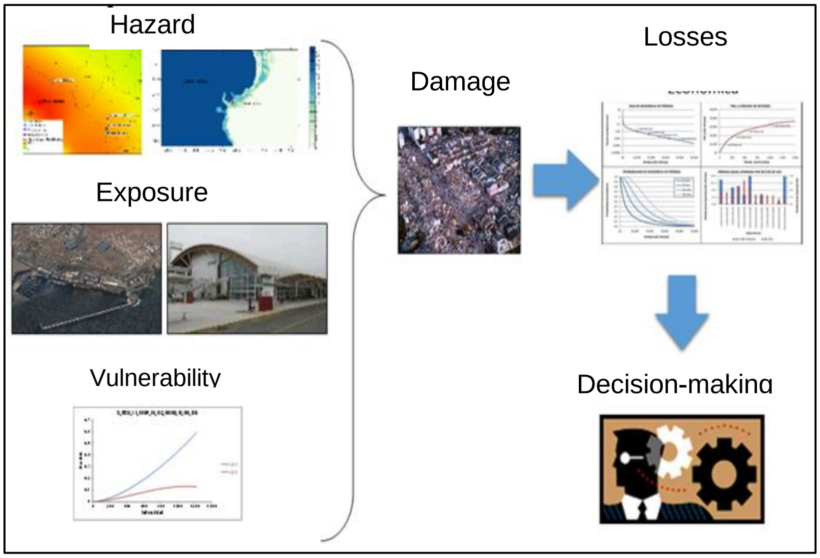

Figure 31. Components of a probabilistic risk assessment

The country risk profiles were developed using the computer program CAPRA-GIS. Established in 2008, CAPRA has as objective to raise awareness in Central American countries of disaster risk and to provide them with a set of tools for a better quantification and understanding of these risks. The initiative started as an alliance between The Central America Coordination Centre for the Prevention of Natural Disasters (CEPREDENAC), the United Nations Office for Disaster Risk Reduction (now UNDRR), the World Bank (WB) and the Inter-American Development Bank (IADB). The computer program, CAPRA-GIS allows to obtain the LEC, which corresponds to the input data for the methodology presented in this study.

To obtain the LEC for the initial and mitigated states in the domain under study (e.g., a country), it is necessary to define the vulnerability functions for all the building typologies that represent the exposed elements (infrastructure), both in their initial and mitigated states. Once the vulnerability functions that represent the initial and mitigated states are available, two separate probabilistic risk assessments need to be performed (one for each state), yielding two different LECs.

Within the scope, available time and resources for the development of this study, the derivation of vulnerability functions for the initial and mitigated states of multiple building typologies in Latin America was not contemplated. Because of this, the results from a comprehensive literature review and the use of criterion and experience of the authors of this report, are used to propose a mitigation proxy that is to be used only in cases where the decision-maker does not have the minimum data necessary to perform the analysis. The proposed mitigation proxy is described next.

Proxy

Objective: to apply the methodology (parametric transformation vectors) to consider the benefits of the risk mitigation measures described in this report. General and empirical types of risk mitigation measures are analyzed, according to their expected loss reduction.

When to use them: its use is only recommended in the absence of the minimum required data to apply the model, such as:

- LEC for the analyzed infrastructure in its mitigated state.
- Cost of implementing the risk mitigation measures.

Considered hazards: earthquakes and floods because the country risk profiles developed by the IADB have mainly focused on these perils.

Earthquake

Proxy vulnerability analysis

The implementation of structural risk mitigation measures is reflected in lower damages and losses in the exposed buildings, which can be represented through variations in the vulnerability functions (see Figure 32). As previously explained, a vulnerability function defines the distribution of losses as a function of the intensity produced by a given hazard. After implementing a risk mitigation measure, the vulnerability function of the exposed asset will displace to the right (with respect to the initial state). This represents lower losses for the same hazard intensity if compared to the initial state.

Figure 32 shows four vulnerability functions. The first one corresponds to the initial state, whereas the other three correspond to the low, medium and high mitigation levels.

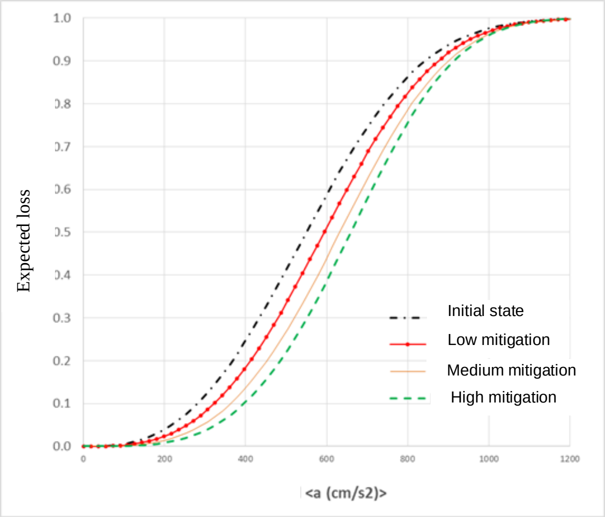

Figure 32. Vulnerability functions for different earthquake mitigation levels

The proposal for the representative mitigation states, obtained after assessing the initial condition of the assets, is based on incrementing, on each case, the resistance and strength (with respect to the initial state) of the point that represents an expected loss of 50% in the following manner:

- Low mitigation level: 8% increase with respect to the initial state.
- Medium mitigation level: 15% increase with respect to the initial state.
- High mitigation level: 20% increase with respect to the initial state.

The resistance increases percentages proposed herein were the result of a calibration process on which the behavior of the LEC was reviewed, in conjunction with the congruence of the loss variations for selected return periods and the associated AAL reduction.

The proxy vulnerability functions were adapted to the specific format required by the computer program CAPRA-GIS, which was used to obtain the LEC for the different cases that were analyzed in this study.

Probabilistic risk assessment results for earthquake (proxy)

After performing the probabilistic risk assessments for the three proxy earthquake mitigation states, the LECs shown in Figure 33 were obtained.

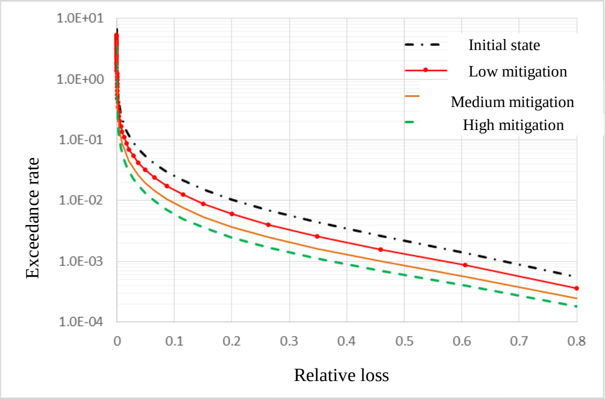

Figure 33. LEC for different proxy mitigation states (earthquake)

For carrying out the probabilistic risk assessments considering the three proxy earthquake mitigation states, this study used a recently updated earthquake hazard model for Latin America and the Caribbean (ERN, 2019). The replacement cost, for calculation purposes, was set equal to one million monetary units. Because the results are presented in dimensionless units (as a percentage of the total exposed value), the selection of the currency becomes irrelevant because the CAPRA-GIS program only requires a number.

As explained in section 5.5 of this report, once the exceedance rates for the initial and mitigated states are available, the factors that reflect the weight of the mitigated LECs with respect to the initial case, for any loss level, l_i, can be calculated as:

$$factor_i = \frac{mitigated\ exceedance\ rate\ of\ loss\ i}{exceedance\ rate\ of\ loss\ i} \tag{A1-1}$$

Since each of the obtained LECs has "*n*" points, this will have "*n*" factors that are grouped into a vector as follows:

$$\overline{V_{TS}} = \begin{pmatrix} factor_1 \\ factor_2 \\ factor_3 \\ \vdots \\ factor_n \end{pmatrix} \tag{A1-2}$$

The graphical representation of the proxy mitigation vectors obtained for the case of earthquakes is shown in Figure 34.

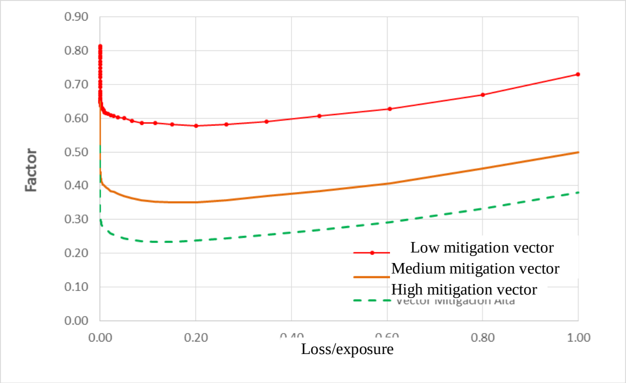

Figure 34. Parametric transformation vectors for different proxy mitigation states (earthquake)

Flood

The development of the parametric transformation vectors for the case of flood risk mitigation used the same methodology for earthquakes but using specific data for this hazard.

Proxy vulnerability analysis

The implementation of flood risk mitigation measures has a wide range of possibilities and is closely related to the local characteristics of the flood prone area under study. According to FEMA (2009), some of the possible risk mitigation measures for loss reduction are elevation of the ground floor of buildings, adaptation of buildings to allow flooding in some areas, relocation of buildings, adaptation of constructions with impermeable barriers and building flood walls, among others.

Detailed knowledge on risk mitigation measures that are suitable to the characteristics of a region requires the development of detailed studies and a large amount of local data, which is possible only for specific projects in small areas. The great variety and specific characteristics of risk mitigation measures for floods cannot be included in a large-scale assessment, such as the one performed in this study. Therefore, flood risk mitigation measures considered in this model consist of elevating the exposed buildings to a given height, measured from ground level, which in principle has a similar effect than building a dike or a wall that prevents a certain flood level. This assumption is deemed reasonable given the base available information to be used as input data in the development of the methodology. The cost of implementing the mitigation measures depends on the exposed value (i.e. the value of the constructions analyzed in the country risk profiles developed by the IADB).

Analogous to the case of earthquakes, Figure 35 shows the results of implementing flood risk mitigation in terms of new vulnerability functions for three mitigation levels: low, medium and high. Figure 35 also includes the vulnerability function that represent the initial state.

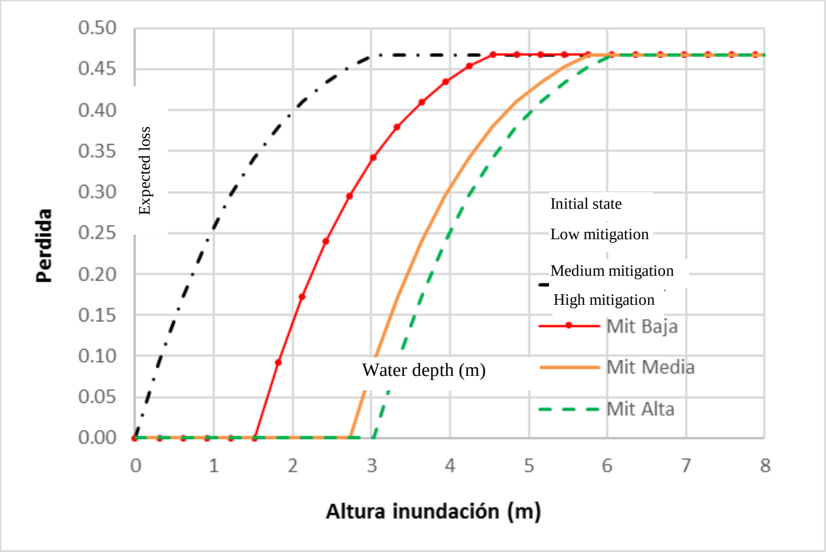

Figure 35. Vulnerability functions for different proxy flood mitigation states

If all buildings are assumed to lie at ground level in their initial state, the following elevations with respect to ground level were used for the considered mitigation options:

- Low mitigation level: 1.5m
- Medium mitigation level: 2.5m
- High mitigation level: 3.0m

The values for elevating the buildings proposed herein, were the result of a calibration process on which the behavior of the LEC was reviewed in conjunction with the congruence of the loss variations for selected return periods and the associated AAL reduction.

Again, the proxy vulnerability functions were adapted to the specific format required by the computer program CAPRA-GIS, which was used to obtain the LECs of the different examples that were analyzed.

Probabilistic risk assessment results for floods (proxy)

The LEC for each mitigation level was obtained after performing a probabilistic risk assessment and are shown in Figure 36.

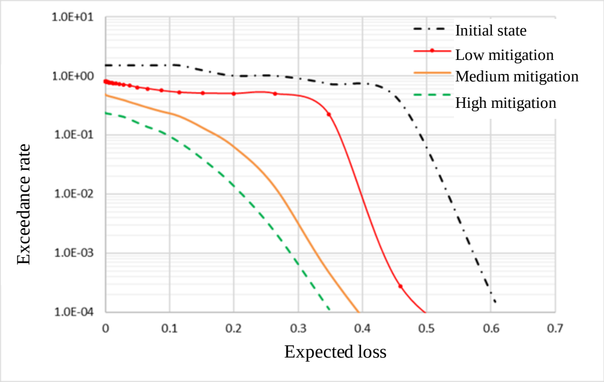

Figure 36. LEC for different proxy mitigation states (flood)

Once the exceedance rates for the initial and mitigated states are available, the factors that reflect the weight of the mitigated LECs with respect to the initial state for any loss level, l_i, can be calculated. Figure 37 shows the transformation vectors for the considered mitigation levels. The obtained results were reviewed and adapted for the case studies in the pilot countries where this methodology was applied.

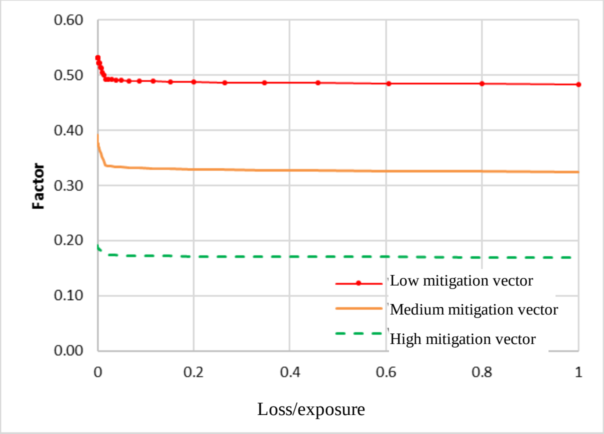

Figure 37. Parametric transformation vectors for different proxy states of flood mitigation

Proxy cost of implementing the risk mitigation measure

The implementation of a risk mitigation measure, either by building a new structure (e.g., flood wall or dyke) or by retrofitting an existing one, implies assuming the costs associated to the materials and workforce necessary for its design and construction. The development of detailed cost estimates for the construction of engineering works (mitigation measures), requires a significant amount of time and specific information about what is to be built. This is an arduous task for punctual measures which are out of the scope of studies where large-scale estimations are made – for example in national strategies. Therefore, using results documented in the existing literature reviewed and expert criteria based on previous experiences, remain being the best options for an approximate solution to this shortcoming.

When implementing a structural risk mitigation measure to an existing construction, its cost can be quantified as a percentage of the initial cost of the asset. Depending on the type of measure to be implemented, its cost can vary from a very small percentage of its initial cost (which can be associated to low impact actions), to higher percentages in the event of mitigation measures with larger scale (which can be associated to high impact actions).

In the country risk profiles developed by the IADB, data on the economic appraisal of the exposed infrastructure is available. In this report, this data is referred to as exposed value, representing the replacement cost of the analyzed infrastructure. Therefore, if a risk mitigation measure is to be implemented in the exposed assets, the mitigation costs can be quantified as a percentage of the cost of the infrastructure in its initial state. In the absence of detailed and specific data on the cost of mitigation measures, a viable solution is to perform a comprehensive review of international experiences on this field and, based on this, propose a representative extra percentage for the cost that corresponds to implementing a risk mitigation measure.

Earthquake

Regarding earthquake risk mitigation measures, the proposed parameter that represents the effects of implementing them corresponds to the resistance of the structural elements. For this reason, a function to calculate the cost of the mitigation measure, based on the resistance increase, is proposed. Vargas and Jara (1989) analyzed the construction cost of designing a building to withstand vertical loads only (reflecting the initial state in this study), as well as after increasing the resistance values to different levels (reflecting the mitigation states herein), and are represented through a seismic coefficient, sc. An increase in sc is reflected on an increase in the resistance of the structure when moving from a non-seismic design, to a seismic one. The values used for sc for the three mitigation levels are:

- Low: sc=0.16
- Medium: sc=0.32
- High: sc=0.40

After reviewing the construction cost information for different seismic coefficients published by Vargas and Jara (1989), it is possible to obtain the following expression that relates the cost, *c* with the structural resistance, *r*.

$$c = 0.41r + 0.59 \tag{A1-3}$$

where *c* is the ratio of the final cost after implementing the mitigation measure with respect to the initial cost of the structure. Figure 38 shows the proposed function.

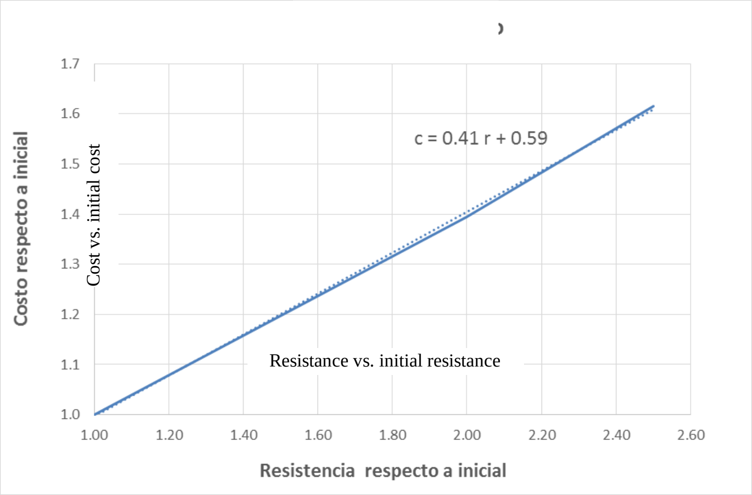

Figure 38. Cost vs. resistance function

Table 43 summarizes the results of the cost increase after considering different mitigation levels, together with the potential loss reduction in terms of the PML and AAL.

Table 42. Cost of the mitigation measures for different increases of resistance, and potential loss reductions in terms of PML and AAL obtained in this proxy analysis

Earthquake			
Impact of the Mitigation Measure	Low (%)	Medium (%)	High (%)
Increase in resistance with respect to the initial state	8	15	20
Cost of the mitigation measure with respect to the exposed value	3.3	6.2	8.2
Potential reduction in PML compared to the initial state (in %)	14 to 37	30 to 60	43 to 73
Potential reduction in AAL compared to the initial state (in %)	39	61	73

The results obtained for the relationship between resistance and cost, as well as the other figures included in Table 43, are within the ranges associated to the implementation of mitigation measures reported by studies that were part of the literature review, these are : Smyth et al. (2004a; 2004b), Michel-Kerjan et al. (2013), Hayes et al. (2013), Thiel and Hagen (1998) and Dennemann (2009).

For instance, Hayes et al. (2013) studied the required cost to increasing seismic resistance in buildings in Memphis, Tennessee. This study was based on comparing the requirements and associated costs for different structural designs between the national and local building codes, with and without resistance for lateral loads. According to the results of the study, the increase in the construction cost after increasing the resistance required by seismic design was, on average, equal to 5.2% of the initial construction cost. The study also indicated that, although the increase in the resistance required by seismic design with respect to its non-seismic state is significant, the additional costs only represent a small percentage of the initial value. The maximum percentages of increase in the construction cost found by Hayes et al. (2013) were in office buildings, with values of 14.4% and 19.6%, to comply with the seismic design following the local and national building codes, respectively.

Table 44 shows the information analyzed by Smyth et al. (2004b) in the case study of typical infrastructure of schools in Mexico and other Latin American countries. The percentage of the cost of the mitigation measure with respect to the initial cost of construction was calculated from the information published by Smyth et al. (2004b), obtaining values between 5.0% and 12.5%.

Table 43. Mitigation costs for schools

Asset cost (US$)	Mitigation measure	Mitigation cost (US$)	Mitigation/asset cost (%)
160,000	Steel braces (option 1)	8,000	5.0
	Steel braces (option 2)	20,000	12.5
	Reinforced concrete braces	13,000	8.1

Source *:* Smyth et al. (2004b)

Dennemann (2009) carried out a study of risk mitigation measures to be implemented in bridges. The information of interest for this study is summarized in Table 45, that shows that mitigation costs are always between 2.1% and 8.2% of the initial cost of the infrastructure.

Table 44. Mitigation costs for bridges

Cost of Property (US$)	Mitigation Measures	Mitigation Cost (US$)	% Cost Mitigation/Property
438,237	Steel jacket	36,000	8.2
	Elastomeric bearings	21,912	5.0
	Shear keys	9,000	2.1
	Restrainer cable	11,280	2.6
	Seat extender	23,250	5.3
	Shear keys + seat extender	32,250	7.4
	Restrainer cable + seat extender	34,530	7.9

Source*:* Dennemann (2009)

Flood

In the examples of floods, the mitigation measures were modeled by elevating the constructions with respect to ground level. This approach allows to estimate the cost of the risk mitigation measures based on the cost of the exposed assets, since this value is the only economic amount available as a reference in the country risk profiles developed by the IADB (2014a, 2014b, 2014c).

FEMA's 2009 P-312 methodological guide, includes different mitigation recommendations to reduce possible flood impacts, among which are the following: adapting the constructions to allow flooding in some zones, relocating constructions, elevating the constructions with respect to ground level, adapting the constructions with impermeable barriers and building flood walls, among others.

In the case of elevating the constructions with respect to ground level, FEMA (2009) found an approximate cost of 3.6% of the initial construction cost when the materials used to raise the existing infrastructure were masonry pieces. This cost corresponds to a 2ft elevation above ground level. Each additional foot of elevation will have an additional cost of 0.2% of the initial construction cost (FEMA, 2009).

Applying FEMA's proposal to the proxy values of risk mitigation measures analyzed in this annex (low: 1.5m, medium: 2.5m and high: 3.0m), the costs shown in Table 46 were obtained. That table also includes potential flood risk reduction in terms of PML and AAL, obtained from the proxy risk analyses presented in the preceding sections of this annex.

Table 45. Cost of mitigation measures against floods and potential loss reductions in terms of PML and AAL

Flood			
Impact of Mitigation Measure	Low	Medium	High
Protection height of construction	1.5m	2.5m	3m
Cost of mitigation measure with respect to exposed value	4.2%	4.8%	5.2%
Potential reduction in PML with respect the initial state	21% to 24%	37% to 49%	44% to 62%
Potential reduction in AAL with respect to the initial state	61%	90%	96%

Other costs suggested by FEMA (2009) for raising the constructions are: 6.5% of the construction value plus 1% per additional foot of elevation, when reinforced concrete piles foundations are used, or 4.4% of the construction value and 1.2% per foot of elevation when foundations with footings are needed.

In the revision of the National Flood Insurance Program, Jones et al. (2006) carried out an analysis considering different flood mitigation measures in the USA. One of the study main conclusions was that implementing flood risk mitigation measures through adapting the foundations of the constructions using piles or foundation columns has a relative lower cost – with values between 5% and 10% with respect the initial construction value. This coincides with the flood mitigation cost proxies proposed in this study.

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