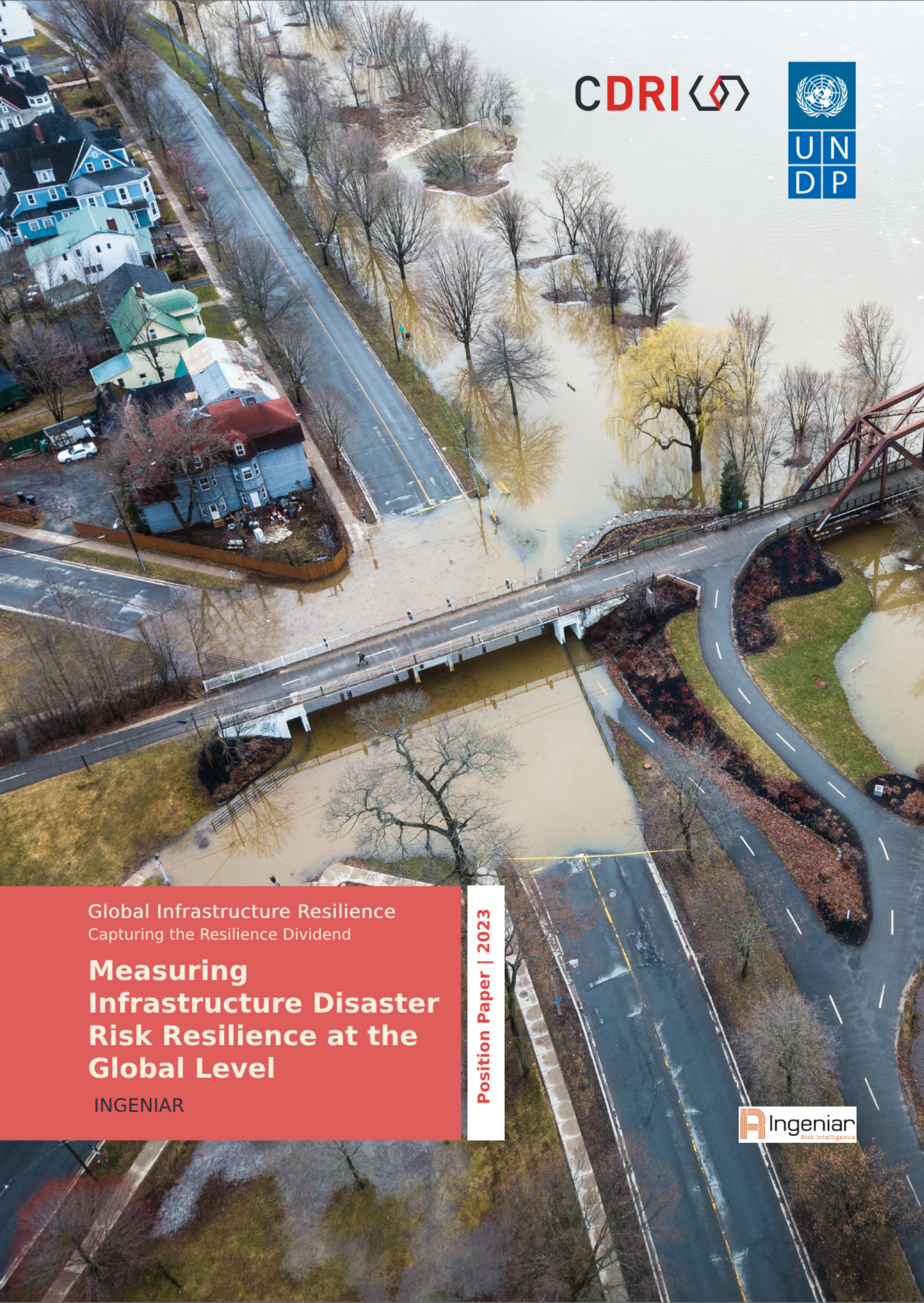

Global Infrastructure Resilience

Capturing the Resilience Dividend

Measuring Infrastructure Disaster Risk Resilience at the Global Level

INGENIAR

Position Paper | 2023

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Risk Intelligence

GIRI: Global Infrastructure Risk Model and Resilience Index

Background report

Measuring Infrastructure Disaster Risk Resilience at the Global Level

CDRI
Coalition for Disaster Resilient Infrastructure

UN DP

August, 2023

Risk Model and Resilience Index Developer

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CONTENTS

1 Introduction

Risk management is all about making effective decisions based on prospective forecasts of uncertain consequences. In many countries, stakeholders usually do not have access to robust risk models and even less to a measure of their uncertainty. As a result, decisions are commonly not well-informed, and their effectiveness is left to chance. It is generally recognized that looking into the past is not enough to make appropriate decisions, not only because of the limited information regarding catastrophic events that occurred in the past but also because, in most cases, the worst events are still yet to occur. Therefore, it is usually not possible to forecast the future consequences caused by hazardous events only based on the information available for the historical disasters.

When looking into the future to assess the possible consequences of upcoming events, all kinds of uncertainties appear to blur the prospective view of the stakeholders, hampering their capability to make decisions. This is the reason why risk assessment should be addressed using analytical probabilistic models that rationally incorporate the related uncertainties and provide uncertainty-sensitive consequence metrics. Only by accomplishing this, the stakeholders shall be empowered to anticipate the occurrence of catastrophic events and their feasible consequences, while considering the uncertainties associated with their estimated severity and frequency.

When looking at the fiscal liability portfolio of a country, the losses caused by disasters are implicit contingent liabilities that increase the fiscal vulnerability of countries. This includes losses suffered by the infrastructure. In other words, a future disaster is an uncertain, hidden public debt that becomes a certain liability when the event occurs. This contingent debt, that represents the potential losses, must be added to the current, explicit debt. If the total value is greater than the present discounted value of future primary surpluses of the country, there is an unbalance in the equation of the country's fiscal sustainability. Governments should therefore recognize that future disasters need to be considered in the country's balance sheets, as they can generate important macroeconomic unbalances.

Therefore, future disasters must be considered a sovereign risk for a country. They, in fact, constitute a risk that must be handled by all the society. To measure this collective responsibility, it is necessary to employ loss assessment models that embed the intrinsic uncertainties of the phenomenon, as well as allow decisions considering the aleatory nature of such losses. It is necessary to produce a quantitative measure of these losses, because "what it is not quantified cannot be managed". The best way of assessing these potential losses is by using probabilistic models, such as the GIRI, which allows governments to measure disaster risk in the context of fiscal sustainability. In this way, it would be possible to identify optimal strategies for vulnerability reduction, retrofitting, and financial protection, in terms of transferring or retaining this sovereign risk. This will allow implementing actions to reduce the losses, minimizing the possibility of insolvency as well as the effects on the development and the quality of life of the population.

1.1 What is GIRI?

The GIRI is CDRI's Global Infrastructure Risk and Resilience Model, and the system of indicators derived from it, covering all countries and territories in the world. Currently, GIRI covers six natural hazards: earthquakes, tsunami, landslides, floods, tropical cyclones, and droughts, the last four include the modification caused by climate change, and therefore provides hydrometeorological risk metrics related to different trajectories of greenhouse gases emissions in the future, in addition to the stationary risk metrics for geological hazard. GIRI currently covers nine infrastructure sectors: power, highways and railways, transportation, water and wastewater, communications, oil and gas, education, health, and housing.

The GIRI, or the Global Infrastructure Risk and Resilience Model of CDRI, is a comprehensive system of indicators that encompasses all countries and territories worldwide. Currently, GIRI addresses six natural hazards: earthquakes, tsunamis, landslides, floods, tropical cyclones, and droughts. The last four include the alterations induced by climate change, thus offering hydrometeorological risk metrics related to various greenhouse gas emission scenarios in the future, in addition to stationary risk metrics for geological hazards. GIRI presently encompasses nine infrastructure sectors: power, highways and railways, transportation, water and wastewater, communications, oil and gas, education, health, and housing. In essence, GIRI possesses the following key attributes:

- It serves as both a metric and a modeling framework to assess disaster risk within the infrastructure systems supporting socio-economic activities. This means it can be adapted to incorporate other hazards and sectors (e.g., windstorms, wildfires, agriculture, ecosystems, etc.). Moreover, it maintains the flexibility to be employed at varying resolution levels, empowering countries to conduct risk assessments at sub-national and local levels, yielding results that are fully compatible and comparable across scales, from global to local.
- It quantifies disaster risk in a fully probabilistic manner, furnishing probabilistic metrics while integrating the influence of climate change through imprecise probability estimates. The inclusion of climate change necessitates a transition from probability theory to random sets theory, marking GIRI as the inaugural global catastrophe risk assessment founded on random sets.
- It incorporates socio-economic context variables that aggravate disaster risk to capture its complex nature and provide the country's resilience performance. Therefore, GIRI provides an operational picture of risk, improving risk knowledge and resilience. An overall risk and resilience landscape will be useful for comparisons and rankings among countries.
- It encompasses events that have yet to occur, not solely historical events. Furthermore, for hydrometeorological hazards, the consideration of climate change-induced modifications challenges the application of a stationarity hypothesis. GIRI stands out as the first global catastrophe risk assessment to incorporate non-stationarity into its modeling and results.

The GIRI's model has three main components: hazard, interpreted as sets of events that are mutually exclusive and collectively exhaustive, i.e., covering all possibilities in which the hazards may manifest in each territory. As abovementioned, the hydrometeorological hazards are modified by climate change; exposure, that is the collection of elements and components of the infrastructure systems and their replacement values; and vulnerability, which relates the intensity of the hazards to the cost of damage for each element. Their appropriate combination using a catastrophe risk modeling process, rooted in random sets theory, provides metrics such as the Loss Exceedance Curve (LEC), the Probable Maximum Loss (PML) curve, or the Average Annual Loss (AAL), that aims at compressing risk in a single number, and it is a convenient metric for comparison purposes. The AAL is the sum of the product, for all the stochastic events considered in the loss model, of the expected losses in a specific event and the annual occurrence probability of that event (Ordaz, 2000; Grossi & Kunreuther, 2005).

Figure 1 shows the risk and resilience assessment framework (Cardona, 1986; Ordaz, 2000; Marulanda, 2013, Bernal et al., 2019). It becomes the basis for the definition of a system of indicators that emulates a *performance curve*, commonly used to express the infrastructure and operational view of resilience.

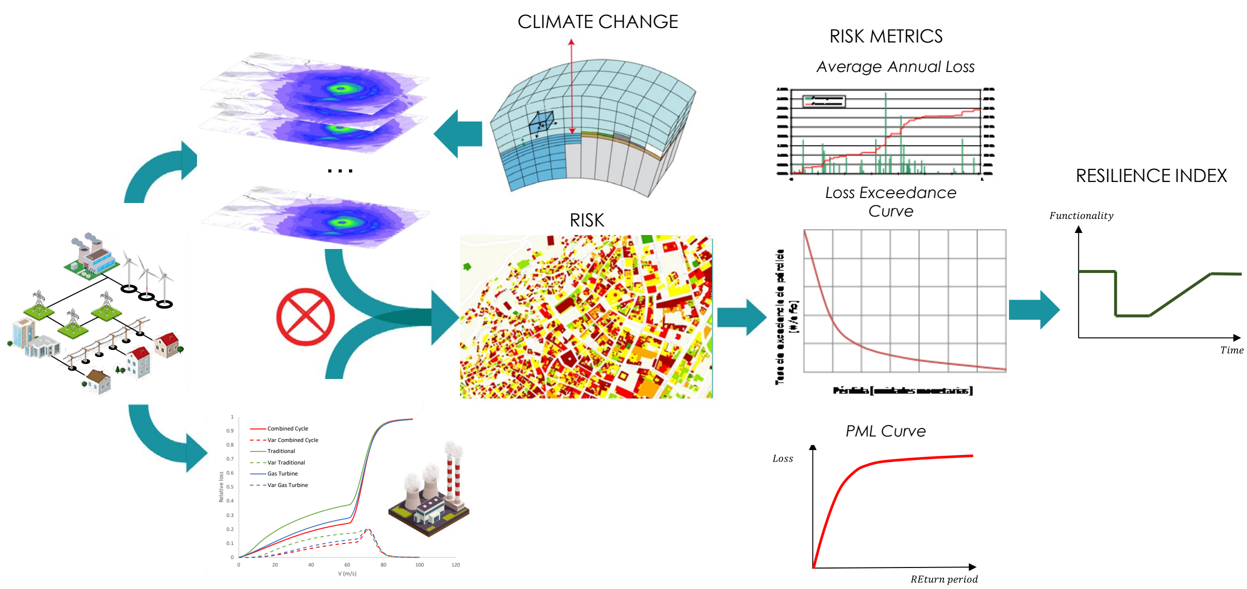

Figure 1. Illustration of GIRI's Model Components

1.2 What is the GIRI Index?

"Assessing Global Progress in Closing the Infrastructure Resilience Gap" entails a tool to gauge the risk and resilience of nations. This tool will undergo regular updates and evaluations to track countries' advancements in enhancing their resilience capabilities. The overarching goal is to introduce an infrastructure resilience index, a valuable resource for gauging a country's ability to withstand ongoing pressures from disasters on lifelines or critical infrastructure.

Effective disaster risk management necessitates not only measuring physical damage and loss but also considering social, organizational, and institutional factors. The challenge in achieving efficient disaster risk management has, in part, arisen due to the absence of a comprehensive conceptual framework for disaster risk. Such a framework would facilitate a multidisciplinary evaluation and intervention. Many existing indices and assessment techniques fail to adequately convey risk and lack a holistic approach conducive to intervention. Various planning agencies responsible for sectors like the economy, environment, housing, infrastructure, agriculture, and health must be informed about the risks specific to their respective domains. This evaluation will concentrate on infrastructure assessment, but it should also cater to the concerns of different levels of government. Local-level risk significantly differs from national-level risk, and each level requires distinct information and decision-making processes. To effectively reduce the impact of disasters, risk information must be presented and explained in a way that captures stakeholders' attention. Thus, it is crucial to employ appropriate evaluation tools that simplify problem comprehension and guide decision-making. Understanding the generation, escalation, and accumulation of vulnerability is fundamentally important. Additionally, performance benchmarks are necessary to provide decision-makers with relevant information and to identify effective policies and actions.

To fulfill these needs and enable the assessment of disaster risk at the national level, the Global Infrastructure Risk Index (GIRI) is proposed. GIRI is grounded in a multi-hazard probabilistic risk assessment and adopts a global holistic approach. This index will rank countries based on their expected Average Annual Loss (AAL) relative to a set of critical economic, financial, environmental, and social development variables.

To monitor countries' progress toward infrastructure resilience, it is essential to define which aspects of resilience can be quantified, along with the indicators and data sources to use. While all dimensions of infrastructure resilience are relevant, asset resilience, given its connection to service disruption and sustainability, is of particular significance. Although service disruption is often more costly than asset loss and damage, it ultimately stems from asset resilience. Thus, the financial risk metrics in the background paper: "Multi-hazard Disaster Risk Model of Infrastructure and Buildings at the Global Level" (Cardona et al., 2023) of this project, measuring risk or the contingent liabilities tied to infrastructure assets, capture the crux of the issue. The risk of service disruption and its implications for social and economic development magnify potential losses and damages.

Measuring infrastructure resilience, therefore, revolves around a country's capacity to design, construct, and manage infrastructure in a way that reduces vulnerability to hazard events and enables swift response and recovery. This measurement makes resilience more concrete and visible to governments, offering added motivation to invest in resilience and reap its benefits.

The composite indicator for measuring infrastructure resilience combines the financial risk metrics of Cardona et al., (2023) with three sets of indicators representing absorptive, adaptive, and transformative capacities to withstand, respond to, and recover from hazard events. This index presents an operational view of resilience grounded in multi-hazard physical risk in infrastructure systems, influenced by various social, economic, and environmental factors. Vulnerability is considered both in its physical dimension, representing susceptibility to damage, and its contextual dimension, expressed through various attributes and variables.

The composite indicator provides a global overview of infrastructure resilience at the national level. However, the same methodology can be applied by countries at higher resolutions, including sub-national and local levels. This approach highlights how probabilistic risk metrics and socio-economic variables can be integrated to identify levers of change for countries to bolster their infrastructure resilience.

2 Measuring Infrastructure Resilience at Global Level

This report proposes an infrastructure resilience index based on a probabilistic and holistic view at a global level, which helps to define the resilience of each country concerning the continuous pressure imposed by disasters on critical infrastructure. Many resilience conceptual frameworks consider diverse shocks but also domains, dimensions, and contexts, such as the social, economic, health, and various others related to development and sustainability. Therefore, there are also multiple definitions and measurement approaches; (e.g., based on analytical and multi-criteria models, dashboards, indexes, or composite indicators and ratings, based on expert opinion or surveys, among other techniques). Regarding disasters, many of these approaches are related to the community, urban centers, environment, climate change, development sectors, networks or lifelines, and critical infrastructures, considering dependencies and territorial levels. Although high-resolution and detailed factors can be included in these technical approaches based on performance and attributes, any resilience assessment will not always be complete and can only be an operational image for monitoring and follow-up periodically, using proxies. This is particularly true when the scope is a national-scale assessment, where only a relative analysis is feasible for disaster risk management, climate change adaptation, and resilience management advocacy.

2.1 Resilience Conceptual Frameworks

Interest in the concept of resilience has been increasing in the last two decades in various domains or dimensions; each one defines it according to their interests and objectives. From its first formal use in material science (Young, 1807; Singer, 1951; Timoshenko, 1953) as ability to absorb impact[1], the concept of resilience has been developed in numerous schools of thought, showing enormous variability and persistent disagreements on its best use (Alexander, 2013; Xue et al., 2018), including ecology (e.g., Holling, 1973; Pimm, 1984, Carpenter, 2001), psychology (e.g., Bonanno et al., 2006), socioecological systems research (e.g., Berkes et al., 2002; Folke, 2006), disaster risk management (e.g., Cardona, 2001; Bruneau et al., 2003; Adger et al., 2005; Cutter et al., 2008), protection technical systems and critical infrastructure (e.g., Boin and McConnell, 2007, Guo et al., 2021; Poulin & Kane, 2021) to name a variety of them. Although a consensus about its definition has not been reached, overall, the resilience notion may help to master challenges posed by various global changes, such as globalization, digitalization, or climate variability (Caralli et al., 2010; Comfort et al., 2010; Bie et al., 2017; Thier & Pot d'Or, 2020); and thus, protect the essential services and assets societies rely on.

The resilience concept has been criticized because it is not always clear what it refers to, and it has been considered a buzzword (Linkov et al., 2014). There are many definitions and also a high variability among them (e.g., Carlson et al., 2012; Biringer et al., 2013; Wied et al., 2020;

[1] Resilience and toughness are properties of materials. The material can absorb the energy of an impact without permanent deformation, in the elastic zone, due to resilience; and withstand impact loads without fracturing, in the plastic zone, due to Toughness.

Mottahedi et al., 2021). That is why it is necessary to decide which framework would be useful to define an assessment approach, considering if it is understood, for example, as a quality, an objective or goal, a process, or a set of capacities. Overall, some authors describe resilience as an ability and others understand it as a performance, outcome, or a process after the disruption of a system. There is also a mixture of action/act and ability/power (Kanno et al., 2019). Many define it more as a measure or degree of something, a rate or speed, e.g., of recovery. However, in recent years, the main view of resilience in the literature has been as a capacity; particularly in the context of infrastructure (Biringer et al., 2013; Wied et al., 2020; Mottahedi et al., 2021).

Regarding disaster risk, UNISDR (2017) defines resilience as "the capacity of a system, community at risk to absorb, adapt, change and withstand the results of hazard in a timely and efficient manner, including through conservation, and the reconstruction of its structures and core functions through risk management". In line with Cardona (2001) and Birkmann et al. (2013), the lack of resilience or social response capacity could also be an element of vulnerability. This can often be determined by the limitation of accessing and mobilizing the resources of a community or a socio-ecological system to anticipate and respond to an identified risk. A comprehensive resilience approach includes risk reduction before the event, coping on time, efficient post-event response and recovery measures, but also adaptation and transformation.

Improving resilience is considered a valid risk-reducing strategy (O'Brien et al., 2006; Birkmann et al., 2013). Concerning capacities of a system, resilience building shows some overlap with vulnerability reduction since the two measures act on "opposite sides of the same coin" (IFRC, 2020; Derakhshan et al., 2022). While the precise relation between vulnerability and resilience is yet debated, there is agreement that resilience is one of the ways to reduce vulnerability (Rose, 2007; Jhan et al., 2020; Mottahedi et al., 2021). However, resilience management is not always concerned with treating specific risks, i.e., increase protection against some known disruptions, but with maintaining and enhancing the ability of the system to absorb, adapt, and recover to any impact under any situation. For many authors, enhancing resilience is, in fact, a more holistic approach to building system capacities, which includes a system's long-term development and its ability to improve itself, particularly due to the adaptive capacity. Therefore, resilience management, in a broad view, puts less emphasis on the reduction of individual risks but focuses on a holistic increase of the ability to deal with disruptions as they emerge (Anholt & Boersma, 2018), emphasizing the recovery, learning, and adaption processes (Gasser et al., 2019).

Specified resilience describes the capacity of specific characteristics or functions of a system to handle specific types of disruptive events (S. R. Carpenter et al., 2012; B. H. Walker & Pearson, 2007). It is also described as the "resilience of what to what" (S. Carpenter et al., 2001) or as the resilience "regarding what" and "against what" (Tamberg et al., 2022), for example, the resilience of crop production to variation in rainfall, or a power system's total production against extreme wind.

2.2 Assessing Vulnerability and Disaster Risk

Sociology and political science define vulnerability as a social construction, resulting from development processes that generate it, thus setting the conditions that transform a hazard into a disaster and exacerbate its impacts. Unlike the hazard, vulnerability accumulates and prevails over time, and it is intricately linked to social aspects and the level of development of the communities. Social situations set a few conditions that, combined with natural event, result in disaster (Oliver-Smith, 2004). Therefore, disaster risk as currently configured is the result of a social process of many years, which derives in the present conditions that can transform a natural event into a disaster, determining whether the exposed elements will be resilient to its effects or are vulnerable to its consequences (Cardona, 2004; Bankoff et al., 2004). Likewise, these current conditions are determining future risk. By tackling these socioeconomic conditions, it is possible to increase the resilience of the communities to cope with the effects of an event, as well as the capacity to quickly recover from the impact and build back better to avoid future disasters. Poor information and communication between social actors, lack of institutional and community organization, weaknesses in emergency response, poor governance, political instability, and the insufficiency of economic wellbeing in a geographic area contribute to increasing risk (Ambraseys, 2010).

Now, from an integrated perspective of disasters, disaster risk has been measured to address the possible economic, social, and environmental consequences derived from events of natural or anthropic threats. This means that disaster risk is not only linked to the occurrence of natural events, but also to the prevailing vulnerability conditions that favor the occurrence of disasters. However, very few analyzes address disaster risk comprehensively and, in most cases, either their focus is mainly only on the physical damage and loss, or they are oriented only towards a social characterization of vulnerability, treating it as equivalent to the risk and not as a condition of susceptibility, leaving aside the potential physical damage that is also essential when it comes to estimating risk. Therefore, the probability of occurrence of a negative impact derived from natural or anthropic events implies the convergence of engineering, social, economic, governance, and political factors that require a holistic approach where the adequate participation of each aspect of the risk configuration is ensured. Risk management decisions must focus on strategies considering both physical damage, direct impacts (hazard dependent), and socio-economic factors (non-hazard dependent) contributing to second-order effects and intangible impacts.

Several methods are proposed based on indicators and figures to assess vulnerabilities and disaster issues. Contributions of Cutter (1994), Bates (1992), Tucker et al. (1994), Davidson (1997), Puente (1999), Cardona and Yamin (1997), Cardona (2001), Barbat and Cardona (2003), Cardona et al. (2003 a, b), UNDP (2004), the World Bank (2004), Carreño et al. (2005, 2007a, 2017, 2018), Salgado et al. (2016), Jaramillo et al. (2016) among others, have attempted to measure vulnerability and risk-related aspects using quantitative or qualitative indicators. In the abovementioned research, vulnerability or disaster risk is evaluated from different points of view, using techniques that are, certainly, similar in method but different in purpose and scope. There are just some techniques supported on indicators to assess or follow-up disaster risk management or resilience; a variety of them are approaches like those described by Khazai et al. (2015), Lacambra and Guerrero (2017), and JRC (2017).

The objective of the holistic risk assessment is to evaluate risk from a comprehensive perspective, integrating physical risk, or potential physical damage, linked to the happening of hazard events, and socioeconomic and environmental factors, non-hazard dependent. This approach seeks to capture how these latter factors have an incidence on physical risk, exacerbating the negative impacts of a dangerous event, as well as affecting the capacity of the society to anticipate or resist, or to respond and recover from adverse impacts. Holistic evaluations of risk have been performed at the city level in recent years by Carreño et al. (2007a); Birkmann et al. (2013); Marulanda et al. (2013); Jaramillo (2014); Salgado-Gálvez et al. (2016), as well as at country level by Daniell et al. (2010); Burton & Silva (2014); and, at global level, such as the GAR Atlas for UNDRR (2017) developed by INGENIAR: Risk intelligence. This approach has also been integrated into toolkits, guidebooks, and databases (Burton et al., 2014; Khazai et al., 2015). Most recently, a study based on the conceptual approaches of this methodology was carried out in Colombia under the framework of the Risk Atlas (UNGRD et al., 2018, Marulanda et al., 2022) and in the USA by FEMA (2020), (Zuzak et al., 2022).

2.3 Risk Management Effectiveness

Disaster risk reduction and adaptation to climate variability and change considering economic, social, and environmental issues, are the objectives of integrated, interdisciplinary, and multi-sectoral disaster risk management. Sustainability and transformation of development are only possible if there is an appropriate strategy of vulnerability reduction and resilience improvement, i.e., through governance strengthening and, particularly through its capacity to anticipate and absorb impacts; capacity to prepare and respond; and capacity to recover and adapt after disasters. The only due to assess resilience is to implement a way for evaluating the performance and effectiveness of disaster risk management.

One way to evaluate that effectiveness is by providing a measure of the performance degree of disaster risk management (or adaptation) considering a set of achievements using a benchmarking approach. One of these approaches at country level has been the DRMi Disaster Risk Management Index (Carreño et al. 2004, 2007b; Cardona, 2005; Cardona et al. 2005; IDEA 2005, Khazai et al., 2015, BID, 2021). The DRMi provides a quantitative measure of the degree and effectiveness of management, supported by predefined qualitative targets that risk management efforts should aim to achieve. The DRMi has been developed using the fuzzy logic approach by defining four general policies, each of which is described by composite indicators. These policies include risk understanding, risk reduction, disaster management, governance, and financial protection. The DRMi has been applied mainly in Latin America and the Caribbean as part of the IDB's Risk and Disaster Management Indicators Program. The DRMi has been an innovative composite indicator for the measurement of the performance and feasible effectiveness of disaster risk management and, in this manner, of the measurement of disaster resilience (Carreño et al., 2018). The methodology has been successful for its purpose at the regional level; however, based on linguistic qualifications and on membership functions, and a process of defuzzification of the qualifications, this method requires surveys and interviews of many experts and officers from different institutions and sectors in each country. This would mean a huge and long effort, taking in mind the resilience evaluation of all countries worldwide, and therefore this approach was discouraged for the development of a resilience index at the global level.

Another way to assess the effectiveness of disaster risk management is risk auditing. It means assessing disaster risk over time to detect whether the risk is increasing or decreasing and therefore the effectiveness of disaster risk management (and adaptation) and its purpose in improving disaster resilience. This approach is mainly useful if it is possible to carry out risk assessments periodically and therefore means benchmarking of the same country over time. These evaluations would be based on the multi-hazard physical risk assessment using probabilistic metrics as obtained with a global risk model, such as the expected loss or average annual loss (AAL), the probable maximum loss (PML), and the rate-on-line (ROL) for an excess-of-loss limit of reference. All of them are based on the loss exceedance curve (LEC). In addition, regarding the evaluation of resilience, the assessment of potential losses, or the prediction of direct effects, provides a notion of the robustness and resistance of the exposure, which is also related to the ability to withstand damage or resist impacts; desirable characteristics associated with the physical quality of exposure, previous retrofitting implementation, and all efforts of the stakeholders made in advance to prevent and reduce physical risk.

2.4 Global Holistic Disaster Risk Assessment

Figure 2 illustrates the conceptual framework used for the holistic disaster risk assessment made for the UN GAR 2017 (UNDRR, 2017). In this approach hazards are events of potential occurrence that have a destructive effect on the built environment (i.e., urban exposure), characterized by the physical vulnerability of human settlements of the countries, and by contextual conditions amplifying or exacerbating physical damages that can be associated with socioeconomic indicators of each country. The convolution of these aspects derives from the likelihood of damage and loss, i.e., a probabilistic risk assessment. The disaster itself is a manifestation of the hazard entailing a disturbed state of the exposure that must also be managed through ex-post measures. Therefore, tackling disaster risk, but also resilience, requires a comprehensive risk management system based upon an institutional structure that supports and promotes public policies, strategies, and corrective and prospective actions addressed to intervene the susceptible elements and conditions of society that favor the setting up or the increment of disaster risk, as well as the created hazards (anthropogenic, technological). Likewise, as part of the disaster risk management and adaptation framework, emergency response and recovery plans and actions based on the resilience performance must be defined, allowing for a quick and effective response when a disaster occurs.

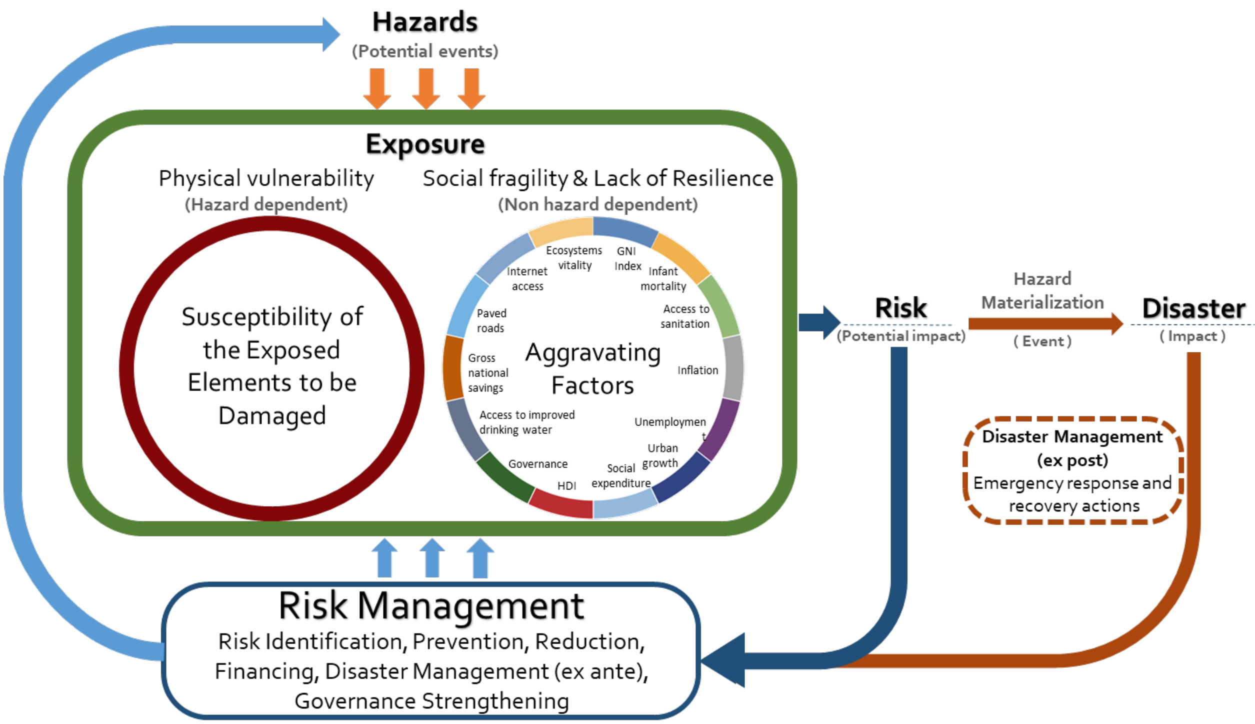

Figure 2. Conceptual Framework of the Holistic Approach to Disaster Risk Assessment and Management (Cardona, 2001); used at UNDRR (2017) and UNGRD (2018).

Thus, this holistic risk and resilience approach robustly addresses the hazard and the contextual conditions, acknowledging their close interrelation, considering both physical aspects and intrinsic characteristics of the society that define either worse or better conditions that, in turn, amplify or reduce the impact of a hazardous event and the capacity of the communities to cope with and recover from adverse impacts. This methodology adheres to the suggestion of Cardona (2001), cited in Bankoff et al., (2004) that vulnerability originates in:

- Physical fragility or exposure: Susceptibility of human settlements to be affected by dangerous events due to their location within the area of influence and their lack of physical resistance.
- Socioeconomic fragility: Predisposition to suffer harm from the levels of marginality and social segregation of human settlements, the disadvantageous conditions and relative weaknesses related to social and economic factors; and
- Lack of resilience: Limitations of access and mobilization of resources in human settlement and the incapacity to respond when it comes to absorbing the impact.

From this perspective of relative and multicriteria analysis, disaster risk is considered as a summation of a series of potential consequences caused by factors of physical exposure (potential damage and losses) to a given hazard and the underlying factors leading to its implications, and the incapacity to face them. This notion implies that undesired effects can be avoided or reduced if triggering and causal actions are intervened. This assessment considers variables of different classes which treatment is not always easy by using functions. For this reason, it is sometimes necessary to use proxies or “representations”, which may well be indexes or indicators. Thus, it can be said that vulnerability might be described by several components reflecting physical susceptibility and fragility (exposure) -which are dependent on the action or severity of the event- and others that reflect social fragility and economic and governance weaknesses. The same if the intention is to measure resilience, that means to assess using indicators, the incapacity/capacity to anticipate, recover, and absorb the impact, which is not always dependent on or conditioned by the direct effects and impacts of the event but on the governance, preparedness, responsiveness, and the restorative and adaptive operational capabilities.

This methodology already used at the global level (Marulanda et al., 2020; UNISDR, 2017) offers a simplified vision of a multidimensional concept, aiming to facilitate its interpretation from different stakeholders, promoting an articulated frame of social, economic, environmental, and cultural aspects. It is worth noting that indicators, in general, do not identify the measures of disaster risk management since these should be conceived using integrated models. However, the main strength of this approach lies in the possibility to make a retrospective analysis by disaggregating the results to identify the factors that should be prioritized for risk reduction/adaptation actions and assess the (in)effectiveness of measures taken in the past. This approach allows the identification of risk drivers associated with the socio-economic context, going beyond the physical vulnerability of the exposed assets. The results obtained in this evaluation support risk communication and benchmarking across countries promoting effective actions for the intervention of vulnerability conditions measured in their different dimensions related to brittleness, fragilities, weaknesses, and lacks.

2.5 Resilience of Critical Infrastructure

Through the provision and delivery of essential services, networked infrastructure systems are the backbone of modern societies. The services form a collective of infrastructure systems that support other non-networked infrastructure systems that are critical for the functioning of society, including to service people and their homes. Non-networked systems are mainly single asset types, such as a building or a facility, which supports the delivery of a service (hospitals, schools, industrial facilities) (GCA, 2021). However, no infrastructure system exists in isolation. Interdependencies between the assets that make up an infrastructure system mean that infrastructure must be considered as a system-of-systems, (SoS).

Networked infrastructure is explicitly mentioned in SDG: 9 (Industry, innovation, and infrastructure) and at the sectoral level in SDG 6 (Clean water and sanitation), and SDG 7 (Affordable and clean energy). Overall, infrastructure underpins all SDGs to some extent. This means that investing in resilient infrastructure helps to make these systems sustainable and is essential to the achievement of the United Nations’ Sustainable Development Goals. Although, the relationship between the concepts of resilience and sustainability is a topic of discussion, due to the inclusion of resilience goals and targets in the SDGs, resilience has become commonly interpreted as an aspect of sustainability (GCA, 2021).

As it was mentioned above, resilience can be defined as the ability of a system and its component parts to persist in the *face of, adapt to, transform, or recover* from the effects of a hazardous event in a timely and efficient manner – this includes the idea of bouncing back (rebuilding) and bouncing forward (transforming). In the field of safety and security, ISO defines resilience simply as an "ability to absorb and adapt in a changing environment" (ISO 2018a; Rød, et al., 2020) and, on the other hand, regarding the definition of critical infrastructure, in several standards worldwide, including ISO, an accepted definition of critical infrastructure is that it is the set of physical structures, facilities, networks, and other assets which provide services that are essential to the social and economic functioning of a community or society. Examples of critical infrastructure can include but are not limited to, power generation, transmission and distribution, water treatment, distribution and drainage, wastewater and stormwater infrastructure, transportation, gas supply and distribution, telecommunications infrastructure, educational facilities, hospitals, and other health facilities (ISO).

While a wide definition of resilience works well as a baseline, the resilience concept remains multifaceted. Consequently, it is possible to differentiate between several domains of resilience in literature, in which the technological, organizational, and, in part, societal domains are the most relevant for critical infrastructure resilience. These domains inescapably influence and overlap with one another but keeping them analytically separate is nonetheless justifiable; most notably, this is crucial in defining which actor is responsible for a specific action associated with critical infrastructure resilience. Yet there is no consensus on some fundamental questions, most importantly on how resilience could be assessed, tested, and duly enhanced (Rød, et al., 2020). From the mid-2010s, not only in scientific studies but also in related policy documents, the earlier focus related to mere critical infrastructure protection was replaced. Besides, a certain temporal dimension to covering the phases before, during, and after an event was considered if the intention of critical infrastructure resilience management is to enable a system to resist, absorb, and recover from unwanted events. In practice, this means finding ways to assess the existing resilience of critical infrastructure to enhance it (Henry and Ramirez-Marquez 2012; Pursiainen et al. 2016; Rød et al. 2017b). Hence the importance of assessment as the basis of critical infrastructure resilience management.

Commonly accepted metrics are not yet available, although there are many assessment techniques in the current context, such as the Critical Infrastructure Resilience Index (CIRI), IMPROVER Technical Resilience Analysis (ITRA) and Organizational Resilience Analysis (IORA), the Resilience Measurement Index (RMI), the Critical Infrastructure Resilience Evaluation (CIRE), the Benchmark Resilience Tool (BRT), the Organizational Resilience Health Check (ORHC), the Resilience Analysis Grid (RAG), the OECD Guidelines for Resilience System Analysis, the Resilience Management and Matrix Audit Toolkit, the Resilience Maturity Model Tool, among many others (Hollnagel 2010; ANL 2013; Lee et al. 2013; OECD 2014a; AIIC 2016; SMR Project 2017; RESILIENS Project 2016; Pursiainen et al. 2016; IMPROVER Project 2017b; Hollnagel 2017; Petersen et al. 2018, IMPROVER Project 2018; Australian Government n.d.).

A review (Rød, et al., 2020) shows that they are usually based on a set of indices, which are then added in a simple cumulative way to form a holistic critical infrastructure resilience index. While some remain simple typologies, others have been developed toward software applications already in use. The techniques differ considerably, especially in such issues as their selected domain of resilience, the required resources, ease of use, outcome in terms of quantitative or qualitative results, the applicability of the results to create enhancement strategies, and so forth. In the final analysis, all techniques have their pros and cons and usually are related to technological, organizational, societal, and economic perspectives; known as resilience dimensions.

Technological dimension mainly refers to the physical properties of the critical infrastructure, focusing on their ability to resist damage and minimizing any loss of function during a crisis, or quickly repairing the unwanted effect (Bruneau et al., 2003; Kahan et al., 2009; Youn et al., 2011; ANL, 2013; Sterbenz et al., 2013; Vlacheas et al., 2013; Francis and Bekera, 2014; Linkov et al., 2014; Labaka et al., 2015; Nemeth and Herrera, 2015; Hosseini et al., 2016; Levenberg et al., 2016; Pursiainen, 2017; Righi et al., 2015; Rød et al., 2017a,b; Ilbeigi and Dilkina, 2017; Barabadi and Ayele, 2018). A quantitative assessment is appropriate in this domain. Technical analysis often requires modeling and simulation tools, integrating the analyses at the system and component level, and incorporating concepts such as reliability, robustness, maintainability, and recoverability (Lounis and McAllister, 2016).

Organizational dimension refers to the organizations that operate and manage the critical infrastructure, including the processes of organizational capacity and capability, planning, training, leadership, communication, and so forth. There is a growing body of literature and certain standards that directly aim at developing indicators to measure organizational resilience (McManus, 2008; ANSI/ASIS, 2009; Kahan et al., 2009; Gibson and Tarrant, 2010; Stephenson 2011; ISO, 2011; Linkov et al. 2013; ANL 2013; ISO 2014c, d, e; Petit et al. 2014; Hosseini et al., 2016; Labaka et al. 2015; Prior, 2015; AIIC, 2016). Organizational critical infrastructure resilience analysis is generally performed qualitatively but can in some cases be transformed into semiquantitative scales, which reflect the maturity of processes that support the resilience related capacities or capabilities.

Societal and economic dimensions are important in critical infrastructure resilience not only because the operators are subject to government regulations, but also in relation to the ability of the economy, civil society, social groups, and individuals to cope with critical infrastructure contingencies. It is therefore related to the needs and tolerances of the community that is dependent on the service provided. Having this information on hand can help operators to identify the minimum required service levels and costs. Most of the efforts have been directed toward development of societal/community resilience indicators (Klein et al. 2003; Chang and Shinozuka, 2004; Flint and Luloff, 2007; Cutter et al., 2008; McAslan, 2010; Sherrieb et al., 2010; Boon et al., 2012; LEDDRA Project, 2014; Aldrich and Meyer, 2015; IMPROVER Project, 2016; Petersen et al., 2017; Rosenqvist et al., 2018). These techniques usually list socioeconomic or institutional-political indicators at a very general level. They can, however, be utilized in defining the preconditions (i.e., societal, and economic context) for organizational and technological critical infrastructure resilience assessment.

Resilience assessment methods can be conveniently grouped as follows: (1) performance-based methods, and (2) attribute-based methods.

Nowadays, the term engineering resilience is sometimes used to refer to frameworks that estimate resilience based on a performance curve as depicted in Figure 3. From this view, resilience underpins adjustment and refers to the ability of a system and its component parts to persist in the face of, adapt to, transform, or recover from the effects of a hazardous event in a timely and efficient manner – this includes the idea of bouncing back (rebuilding) and bouncing forward (transforming).

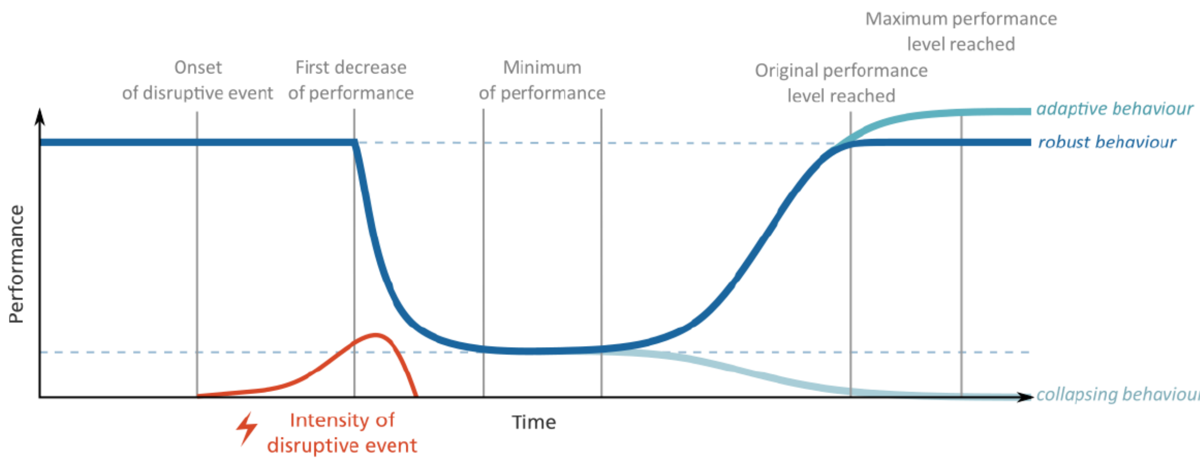

Figure 3. Performance Curve to Assess Resilience. Mentges et al., 2023.

That ability of the system is a resulting set of capacities that consists of (1) the capacity to keep the initial impact of an unspecific disruptive event as small as possible (absorptive capacity), (2) the capacity to recover fast and as completely as possible from disruptions (restorative capacity) and (3) the capacity to learn from disruptions and implement corresponding changes to the system and thus reduce the impact of future disruptive events (adaptive capacity). Also, regarding the same approach, Béné et al. (2012) distinguish absorptive, adaptive, and transformative capacity; but Rehak et al. (2019) distinguish robustness, recoverability, and adaptability; the MCEER's resilience framework (4R) comprises *robustness, redundancy, resourcefulness, and rapidity* (Bruneau et al., 2003); and the US Argonne National Laboratory's framework comprises *preparedness, mitigation, response, and recovery* (Carlson et al., 2012). Overall, despite all these differences in the naming, there is a consensus on the general order and duration of the distinct phases of the performance curve or outcome-based approach. Figure 4 illustrate another schematic representation of an infrastructure or system's performance profile with aging effects used in engineering (Ayyub, 2014a/b,2015). It should be noted that the hazard events have varied intensities and not all events fail the system and disrupt the system's performance (Ayyub, 2021).

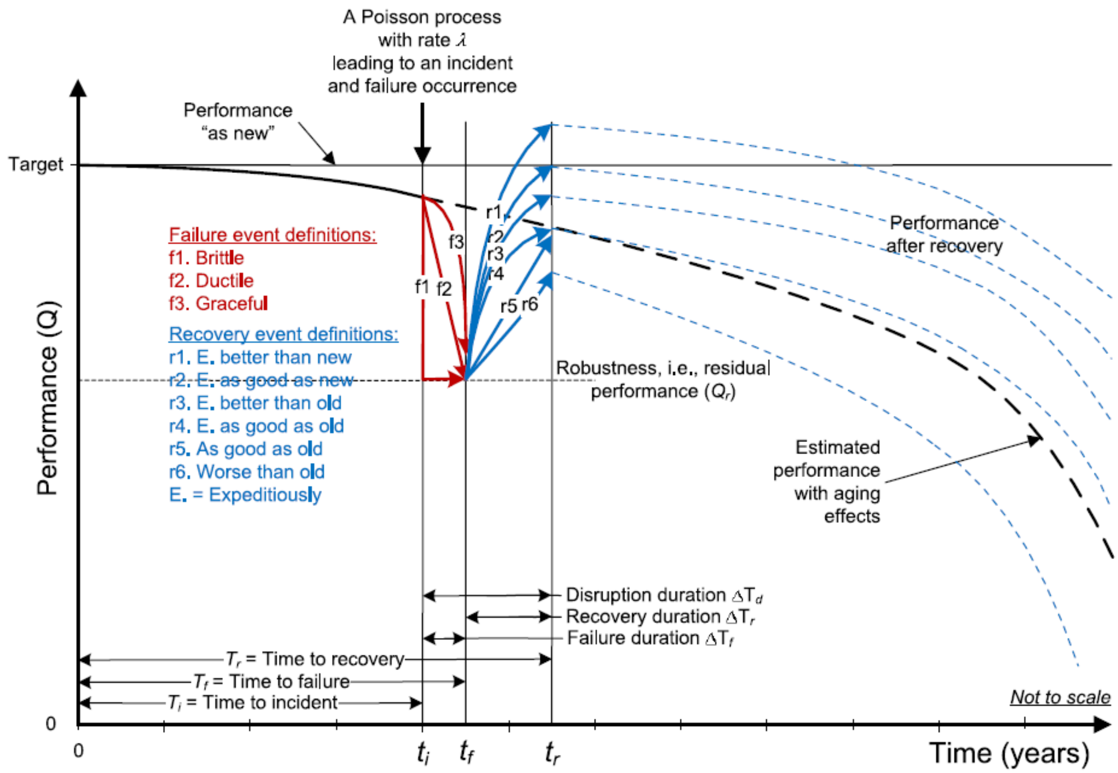

Figure 4. Performance Profile of an Infrastructure or Lifeline System. Ayyub, 2021.

An alternative to performance- or outcome-based approaches (e.g., approaches using the performance curve) is to estimate resilience based on system characteristics which are assumed to build resilience (see, e.g., Asadzadeh et al., 2017 or Cutter, 2016a), i.e., corresponding approaches do not rely on the occurrence of a disruptive event but focus on the system's potential to deal with potential events.

Attribute-based methods generally seek to answer the question "What makes my system more (or less) resilient?" Thus, these methods typically include system properties that are accepted as being beneficial to resilience. Examples of these categories might include *robustness, resourcefulness, adaptivity, and recoverability*. Application of these methods typically requires analysts to follow a process to review their system and determine the degree to which the properties are present within the system. The benefit of these approaches is that their applications tend to be less time and resource-intensive and result in either qualitative or semiquantitative estimates of resilience. Some examples of this type of approaches are the FM Global Resilience Index, (Pentland Analytics, 2022).

In general, distinctions among resilience assessment methods are typically based on quantitative versus qualitative assessment, deterministic versus probabilistic methods, components versus systems, and networks versus systems of systems. Some efforts have attempted to provide, alternatively, general principles regarding resilient systems such as diversity, redundancy, modularity, subsidiarity, buffer storages, geographical dispersion (Thier & Pot d'Or, 2020), cohesion (Fiksel, 2003), feedback, monitoring, leadership, and trust (Carpenter et al., 2012). This is because, perhaps, it would be an easier way to promote standards, but the path toward an approved standard is long, bureaucratic, and political, and the techniques, quite rightly, will always remain contested. While many ISO standards took years to agree on, and editions have been both commended and condemned, the same is probably true of critical infrastructure resilience management. So far, some efforts are being made to this end, both nationally and internationally, for instance at the European Union level, with several resilience projects and approaches joining forces (European Commission 2018) or the ongoing initiative ISO-WD 22372, 2023.

Regarding metrics, it is relevant to say that they can be evaluated directly or indirectly (proxies) or be obtained from models resulting from several measures. Information difficult to access often leads to using indirect metrics or proxy indicator that therefore provide only an approximate representation of reality (Vinchon et al., 2011; Hollnagel 2011a; Shirali et al., 2013). The aggregation of different elements to produce a metric can prove difficult due to the different natures of the elements, the time steps linked to them, their associated uncertainties, etc. The data and information used to measure the metrics are often imperfect (uncertain, imprecise, incomplete, contradictory): such imperfections must be considered to better represent reality. Resilience is strongly linked to the concept of the progression of unknown transitional states not foreseen by the system.

In summary, there is extensive literature on disaster risk and resilience frameworks and measurement methods based on indicators, composite indexes, and other tools and approaches, regarding communities and critical infrastructures. Many of them have been reviewed due to overlap and diversity (Curt and Tacnet, 2018; Gillespie-Marthaler et al., 2018; Dianat et al., 2020; Rød et al., 2020; GCA, 2021; FEMA, 2022; Derakhshan et al., 2022; Graveline and Germain, 2022; Zuzak et al., 2022). In addition, many efforts have been done on regard to the development of glossaries regarding resilience-related terms for critical infrastructure (UNDRR, 2018; Mentges et al., 2023; CDRI, 2023).

3 Global Infrastructure Resilience Assessment

One of the main challenges related to resilience is to find the right ways to communicate complex issues from science to policy and to the public. Composite indicators are a tool to do so as snapshots over time, by offering a simplified representation of a multidimensional concept. They are big pictures that allow an easier interpretation of complex issues. Indicators may highlight at the global level some of the aspects of risk, risk management, and resilience itself, and contribute to the formulation and analysis of public policies and decision-making processes. What is not measured cannot be managed, and therefore for defining a robust strategy for risk and resilience management is the first step to evaluate resilience.

Several key performance indicators should be selected to monitor progress towards achieving resilience. They should be selected based on the key actions the stakeholders will implement. The weightings for the indicators should be determined as some will have more influence on enhancing the infrastructure's systemic resilience depending on the user context.

Risk, adaptation, and resilience are cross-cutting notions and as such, they must be addressed through a comprehensive and multidisciplinary approach. An overall composite index should be, by design, a simplified, summary measure. Practical considerations require that the data are available, quantitative (or quantifiable), global, annual and from credible sources. Data should be sourced from the relevant data custodians, and data sharing should be encouraged throughout the process.

Performance- and attribute-based approaches have their benefits and limitations, but when jointly considered, they have the potential to inform infrastructure stakeholders with a more complete understanding of infrastructure resilience. That is, they can describe not only “How resilient is my system?” but also “What can I do to make my system more resilient?”. Considering both approaches a Global Disaster Resilience Index, GIRI, is herein posed.

Figure 5 presents the diagram used herein to measure the GIRI, considering a set of indicators to reflect i) the capacity to absorb the impact (in the pre-event state), taking into account the intensity of the potential damage and loss, and its amplification by an aggravating factor derived from the socio-economic context and fragilities; ii) the capacity to respond, obtained from aspects related to the efficient reaction, redundancy, business and service continuity (that characterize the post-event degraded state, before start restoration, as the first stage of recovery); and iii) capacity and effort to restore, obtained from aspects that reflect the rapid rehabilitation and reconstruction (second stage of recovery or restorative state), that will enhance the original level of performance due to adaptation and transformation of affected infrastructure and community.

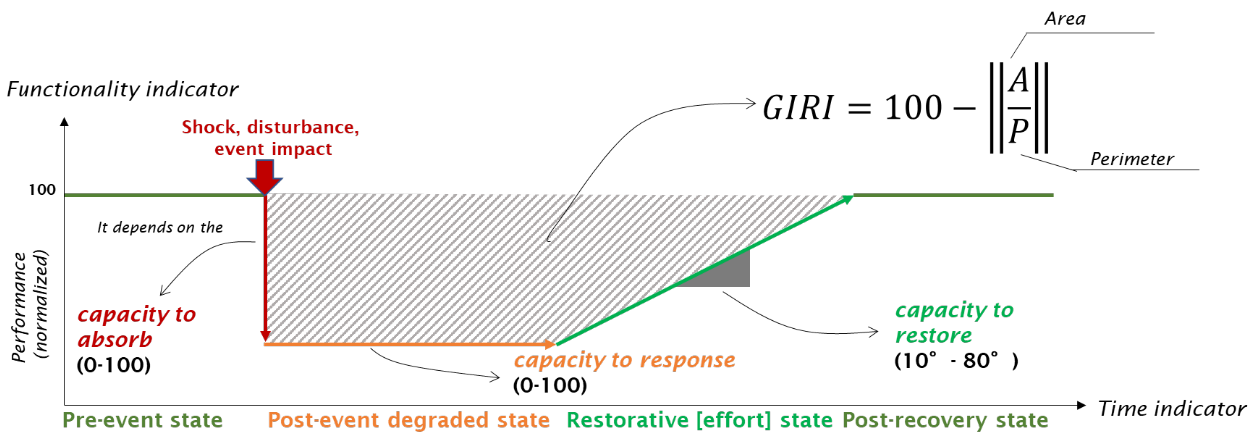

Figure 5. Multi-phase and Multi-capacity Resilience Trapezoid Approach, Analysis, and Measure for the GIRI.

The GIRI adopts relative values between 0-100 based on a normalized score resulting from the division of the area by the perimeter of the resilience trapezoid diagram. The lowest value (0) indicates low overall infrastructure resilience, and the highest value (100) means high overall infrastructure resilience. The GIRI composite indicator can be disaggregated into the three main capacities, each of which in turn can be disaggregated into component indicators.

The capacity to absorb the shock, disturbance, or event impact, is represented as a sudden loss in the performance or capacity of infrastructure assets to provide essential services due to the loss and damage, associated with hazard events. This capacity to resist or withstand is conditioned by physical risk and social and economic variables which may aggravate the potential impact of the hazard events, leading to larger losses in performance.

The capacity to respond is represented as a horizontal line, whose length represents the ability to respond fast and efficiently. The shorter the line, the higher the capacity to respond during the post-event degraded state, when coping and operations are undertaking as a first phase of the total recovery effort.

The restorative stage is assumed to start from the level of the loss in performance until the assets have restored and services full recovered. The inclination of the slope inclination represents better (80°) or worse (10°) capacity to restore fast and efficiently, and this is the second phase of the total recovery effort. This capacity can be represented with other set of indicators related to rapid rehabilitation and restoration, reconstruction, improvement, adjustment, learning, and transformation.

As shown in Figure 6, there are a few advisable qualities, or properties, or principles that infrastructure should hold to be considered resilient. These qualities can belong to all capacities, but they can influence in a higher level, a specific one. On the other hand, indicators may also have an association with all three capacities. Thus, the indicators chosen for each capacity are mechanisms that intend to reflect the core qualities of each capacity and give contextual conditions that might influence those capacities. For instance, the quality of infrastructure indicator in the capacity to resist means that in the case of better-quality infrastructure, built to high standards, the drop in performance is likely to be less than in lower-quality infrastructure. Similarly, countries with significant investments in innovation and technology are likely to experience faster and more efficient recovery compared to countries with lower levels of investment in infrastructure and technology.

Six indicators were chosen, for each capacity, based on their relevance and the availability of publicly accessible, reliable global data in as many countries as possible. Many indicators were not considered because they did not meet these criteria. All indicators were assigned the same weight and were combined as explained below.

The indicators that compose each capacity are normalized to allow their aggregation. For instance, the indicators for the capacity to absorb, and for capacity to respond range from 0 to 100, where the higher values mean a small drop in performance and rapid and efficient response respectively, and lower values mean a high drop and a low and inefficient response respectively. This means an inverse scaling is needed to measure these capacities appropriately.

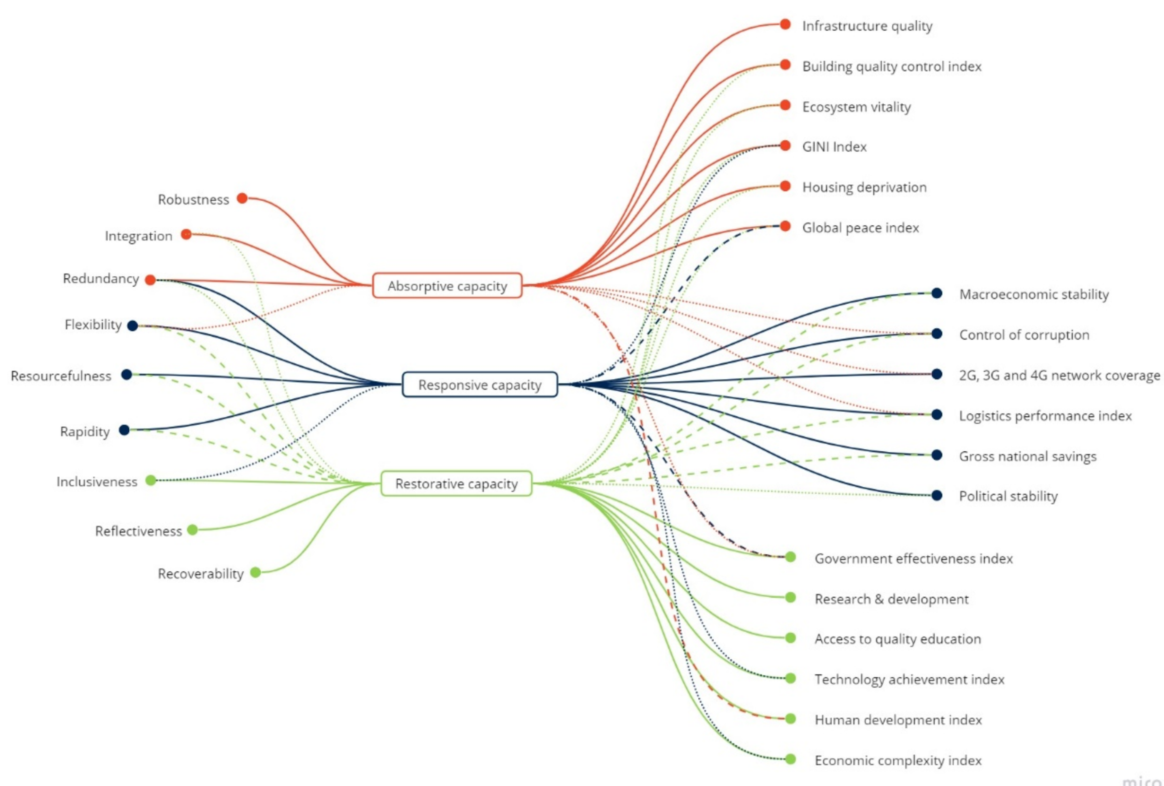

Figure 6. Interconnectedness between the qualities of resilience systems and the three resilience capacities and between indicators

The resulting diagrams shall be the tool to measure resilience in each country based on transformed and commensurable indicators associated to each specific absorptive, responsive, and restorative/adaptive capabilities. A world map can be made as the outcome of the resilience ranking of the countries. In summary, all these issues can be reflected from existing indicators issued for all countries providing an operational picture of the abovementioned capacities.

3.1 Capacity to Absorb

Under this methodology, the capacity to absorb is an inverse figure of disaster risk. The total risk R_T is a function correlating the potential physical damage R_{Ph}, and an aggravating factor F. Physical risk R_{Ph} is obtained from the vulnerability (physical susceptibility) or robustness of the exposed infrastructure to hazards. On the other hand, F depends on how infrastructure quality, social-economic and governance fragilities, lacks, and weaknesses amplify risk, i.e., how prone the infrastructure is to damage and losses, and how the community or society, supported by this infrastructure, can be impacted. Thus, total risk R_T may be understood as the combination of direct physical risk and a measure of additional risk associated with contextual conditions and it is expressed as:

$$R_T = R_{Ph} \ (1 + F) \qquad (1)$$

known in literature as Moncho's Equation, where R_{Ph} and F are composite indicators (Cardona, 2001; Carreño, 2006; Carreño et al., 2007). This expression explicitly incorporates the natural, socio-natural, and anthropic character of the different aspects controlling disaster risk in a single indicator. R_{Ph} is obtained from probabilistic risk models, while F, accounts for the contextual conditions determining the proportion in which the socio-economic context of the area under analysis causes an additional risk to the physical one, i.e., its impact or indirect effects on society. Note that there can be no context-derived risk without physical risk (loss, damage, or direct effects), a characteristic that stems from the comprehensive nature of the holistic assessment. Detailed information about this approach can be found in Carreño (2006); Carreño et al. (2007); Barbat et al. (2011); Marulanda et al. (2020).

The Average Annual Loss (AAL), as described in Annex A, on multi-hazard probabilistic risk metrics, provides an essential input for the capacity to absorb reflecting the physical risk R_{Ph}. The AAL is a robust metric, which condenses in a single number the overall level of disaster and climate risk, internalized in a country's infrastructure. The AAL provides insight into potential loss and damage into infrastructure assets, and thus provides a first window into the capacity to absorb hazard events of different intensity and frequency.

However, while the AAL is a fundamental measure of asset resistance and robustness, total risk R_T is also influenced by other contextual variables, which aggravate the physical risk as abovementioned. The aggravating factor F is obtained by combining a set of context indicators, which influence as amplifiers the impact of hazard events on the infrastructure. The contextual indicators chosen are:

- **Infrastructure Quality**[2]**:** good quality infrastructure will be reflected in a better performance of the assets when a hazard event occurs.

- **Building Quality Control Index**[3]**:** This includes variables such as the quality of regulation, of control before, during and after construction, professional liability and insurance regulation, and certification. Good building quality should indicate better building practices, inherent in infrastructure with higher resistance to hazard events.

- **Ecosystem Vitality**[4]**:** Healthy ecosystems can lead to more sustainable growth of assets and income, economic development, and well-being of people. Ecosystem preservation and restoration can contribute to resilience to climate change and to climate change mitigation. In turn, environmental degradation is a major driver of disaster risk. Low quality and quantity of ecosystem services exacerbates climate change.

- **GINI Index**[5]**:** The GINI index represents the income inequality or the wealth inequality or the consumption inequality within a nation or a social group. Social inequalities can increase vulnerability due to the lack of capacity to cope with an impact of an event. Disasters are a bigger burden in more unequal countries given the lack of affordability to implement preventive measures, or limited access to resources to ensure resilience to events. More equal societies are also more resilient. Flatter hierarchies lead to higher cooperation among individuals (Germano and Demetrius, 2014).

- **Housing Deprivation**[6]: Reflects social and economic inequality and the capacity of governments to deliver safe and affordable housing (SDG11). High rates of housing deprivation are likely to be reflected in significant parts of the population living in unplanned and unregulated settlements with precarious infrastructure with a low capacity to resist hazard events.

- **The Global Peace Index, GPI**[7]**:** The index considers international and domestic conflict, social safety and security, and militarization. A positive value may indicate outcomes such as higher per capita growth, better environmental performance, less civil conflict, or violent political shocks, as well as infrastructure with higher resistance.

[2] FM Global Resilience Index. https://www.fmglobal.com/
[3] Doing business legacy. https://www.worldbank.org/en/businessready/doing-business-legacy
[4] Component of the Environmental Performance Index, EPI. Yale University. https://epi.yale.edu/
[5] The World Bank. https://data.worldbank.org
[6] Oxford Poverty and Human Development Initiative. https://ophi.org.uk/
[7] visionofhumanity.org

3.2 Capacity to Respond

Also, a holistic approach of capacity to respond can provide a way to reflect features related to preparedness, monitoring, and warning, efficient reaction, mobilization and coping, redundancy, and business and service continuity, using a set of socio-economic and governance indicators. The indicators chosen to represent the capacity to respond represent how well a country performs in disaster response.

- **Macroeconomic Stability**[8]: measures how robust an economy is. A strong economy means that a government will have more resources available for effective and timely response without having to increase indebtedness.

- **Control of Corruption**[9]**:** Corruption may erode the financial resources available to respond to infrastructure failures and undermine capacities for service restoration.

- **2G, 3G and 4G Network Coverage**[10]: Access to wireless communication directly influences effective and timely disaster response. Better network coverage can allow authorities to access real time information on the distribution of asset loss and damage and service disruption and can facilitate communication between affected households, communities, businesses, and the different stakeholders involved in response, including utility providers, emergency services and others.

- **Logistics and Performance Index**[11]**:** The LPI consists of both qualitative and quantitative measures and helps build profiles of logistics friendliness for these countries. It measures performance along the logistics supply chain within a country. Emergency response requires proper, structured, standardized, and organized logistics in order to respond efficiently and fast. LPI is considered as a vital element in economy's competitiveness (Arvis et al., 2007). It is related to businesses and gives an understanding on how well countries do in terms of logistics processes, logistics environment and institutions, constraints hindering smooth flow of logistics activities present at ports, borders or inside the country. Six areas compose the index: 'infrastructure', 'services', 'border procedures and time' and 'supply chain reliability'. Underdevelopment of logistics can result in aggravated trade costs and hinder smooth flow of goods because of impoverished infrastructure, poor transportation facilities and uncontrolled bureaucracy of the state institutions. Underdevelopment of logistics can result in underperforming in emergency response due to the incapacity to handle an event fast and efficiently.

[8] Element of the prosperity index composed by GDP per capita growth (The World Bank) and Inflation Volatility (International Monetary Fund).
[9] Component of the World Governance Indicators. The World Bank. https://info.worldbank.org/governance/wgi/
[10] Groupe Speciale Mobile Association. https://www.gsma.com/
[11] The World Bank. https://data.worldbank.org

- **Gross National Savings**[12]**:** The national savings rate measures the amount of income that households, businesses, and governments save. It looks at the difference between the nation's income and consumption and is a gauge of a nation's financial health, as investments are generated through savings. GNS is a gauge of a nation's financial health, as investments are generated through savings. Gross National Savings can serve for both, access to resources in case of emergencies, or as a backup to borrow economic resources to respond to emergencies.

- **Political Stability**[13]: Political stability and absence of violence measures perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically motivated violence and terrorism. Political instability and violence may undermine response efforts due to the difficulty to access resources, to the lack of strong institutions, that avoid the rapid and efficient interventions.

3.3 Capacity to Restore

The capacity to restore reflects how well a country can recover from asset damage and service disruption. The better the performance the steeper the line. This is directly related to how deep is the drop in the capacity to resist and absorb. However, it does not really depend on the length of the response line. The indicators chosen for the capacity to restore with adaptive and transformative abilities to improve the forward infrastructure resilience are:

- **Government Effectiveness Index**[14]: captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. This index reflects the capacity of a government to plan and manage a robust recovery of infrastructure assets and essential services.

- **Research & Development**[15]: According to the OECD R&D intensity is one of several indicators used to measure progress toward achieving the UN Sustainable Development Goal (SDG) 9 on innovation. SGD Goal 9 seeks to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

- **Access to Quality Education**[16]**:** Access to quality education leads to a country with a higher productivity and therefore a country with a stronger economy. Access to quality education ensures the presence of high qualified professionals that will work towards a robust and quick recovery of infrastructure and services.

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[12] The World Bank. https://data.worldbank.org

[13] Component of the governance indicators. The World Bank

[14] Component of the World Governance Indicators. The World Bank. https://info.worldbank.org/governance/wgi/

[15] World Intellectual Property Organization. https://www.wipo.int/portal/en/index.html

[16] Component of the prosperity index. Legatum Institute. https://www.prosperity.com/

- **Technology Achievement Index**[17]: Reflects the country's technological capacity, including associated human resources. Access to new or enhanced technologies will normally speed up recovery, including the opportunity to use the recovery process to introduce innovations.

- **Human Development Index**[18]**:** The Human Development Index is a statistic composite index of life expectancy, education, and per capita income indicators. Components of the human development index such as poverty reduction, quality of education, affordable housing, social equity and equality, food security, aim to reduce vulnerability of communities (Raikes, et al. 2021, Hallegatte et al., 2020, UNDP, 2020, Lewis, 2012, UNDP, 2004).

  High HDI can reflect better levels of education, which is important for developing cognitive and critical skills and scientific knowledge to be better informed. Better health systems that allow a continuous and more sustainable provisions for ensuring a better recovery. Good income levels can reflect availability of savings, access to credits, insurance, that will help to recover faster and more efficiently.

- **Economic Complexity Index**[19]: Reflects the overall state of the economy of a country and therefore its capacity to successfully recover from hazard events.

Infrastructure resilience today is the result of decisions and actions of the past. However, resilience can be enhanced, if the underlying factors that condition its capacity to resist and absorb, respond, and restore, and then also recover are modified. That is why it is important to treat resilience as a performance characteristic instead of an attribute of the state of a system. The former option creates incentives for action, while the latter may lead to inertia and inaction.

The GIRI can be used to monitor how capacities change over time, which in turn can be disaggregated by the indicators that compose each capacity. Understanding resilience as a performance characteristic allows improves understanding of the dynamics of change in each country.

3.4 Summary of the GIRI Results

3.4.1 The GIRI Assessment

The Global Index of Resilience to Disaster Risk (GIRI) is showcased in two distinct formats: one as a singular numerical value and the other as a graphical curve. The numerical value serves as an indicator of resilience, signifying the ratio of the area enclosed by the three capacity measures to

[17] Desai et al. 2002
[18] UNDP, Human Development Reports. https://hdr.undp.org/data-center/human-development-index#/indicies/HDI
[19] Observatory of Economic Complexity. https://oec.world/

the sum of these capacities. This quantitative representation facilitates the ranking of countries based on their resilience levels. However, the graphical curve format provides a more comprehensive insight into a country's behaviour concerning disaster risk resilience. It also offers a clearer visualization of how physical risk and infrastructure gaps influence both the value and shape of the GIRI curve.

3.4.2 Infrastructure Gap

The infrastructure gap[20] is defined as the difference between the existing infrastructure and infrastructure needs. The gap reflects implications that are not necessarily reflected in the risk metrics, for example:

- *Inadequate infrastructure capacity:* Insufficient capacity in infrastructure assets to provide essential services and support social and economic development. This vulnerability exacerbates the impacts of hazards.
- *Infrastructure obsolescence:* Outdated or obsolete infrastructure, exceeding its design life, is more prone to failures and collapses. Neglecting maintenance, modernization, and upgrades makes it fragile and less resilient against threats.
- *Limited diversification and redundancy:* A substantial infrastructure gap hampers system redundancy, leading to increased dependence on individual infrastructure assets and heightened vulnerability.
- *Prolonged recovery:* A significant infrastructure gap can extend the recovery time following adverse events, owing to limited resources and recovery capabilities.

In the GIRI assessment, the infrastructure gap factor was utilized to adjust risk metrics. Essentially, the infrastructure gap represents the percentage of GDP that represents the difference between actual investment and the investment needed to bridge this gap. This percentage of GDP serves as a multiplier for the average annual loss, consequently affecting the physical risk value. To address data discrepancies and missing information for certain countries, regional and income group averages were computed to assign values.

Countries with very low infrastructure density may appear to have minimal risk, but this often reflects low exposed value or outdated infrastructure rather than high physical resilience. Factoring in the infrastructure gap corrects for this distortion.

[20] The infrastructure gap is expressed as a percentage of GDP. The data has been sourced from the Global Infrastructure Hub, Asian Development Bank and Infralatam. Due to significant variations in the information and the absence of data for certain countries, regional and income groups averages were calculated to assign values to countries with missing information. For African countries, the African Infrastructure Development Index provided by the African Development Bank was used to adjust the derived factor from the average.

Figure 7 illustrates the transformation of risk metrics after incorporating the infrastructure gap factor. Nations with higher infrastructure density experience less pronounced changes in their physical risk values compared to countries facing a substantial infrastructure gap.

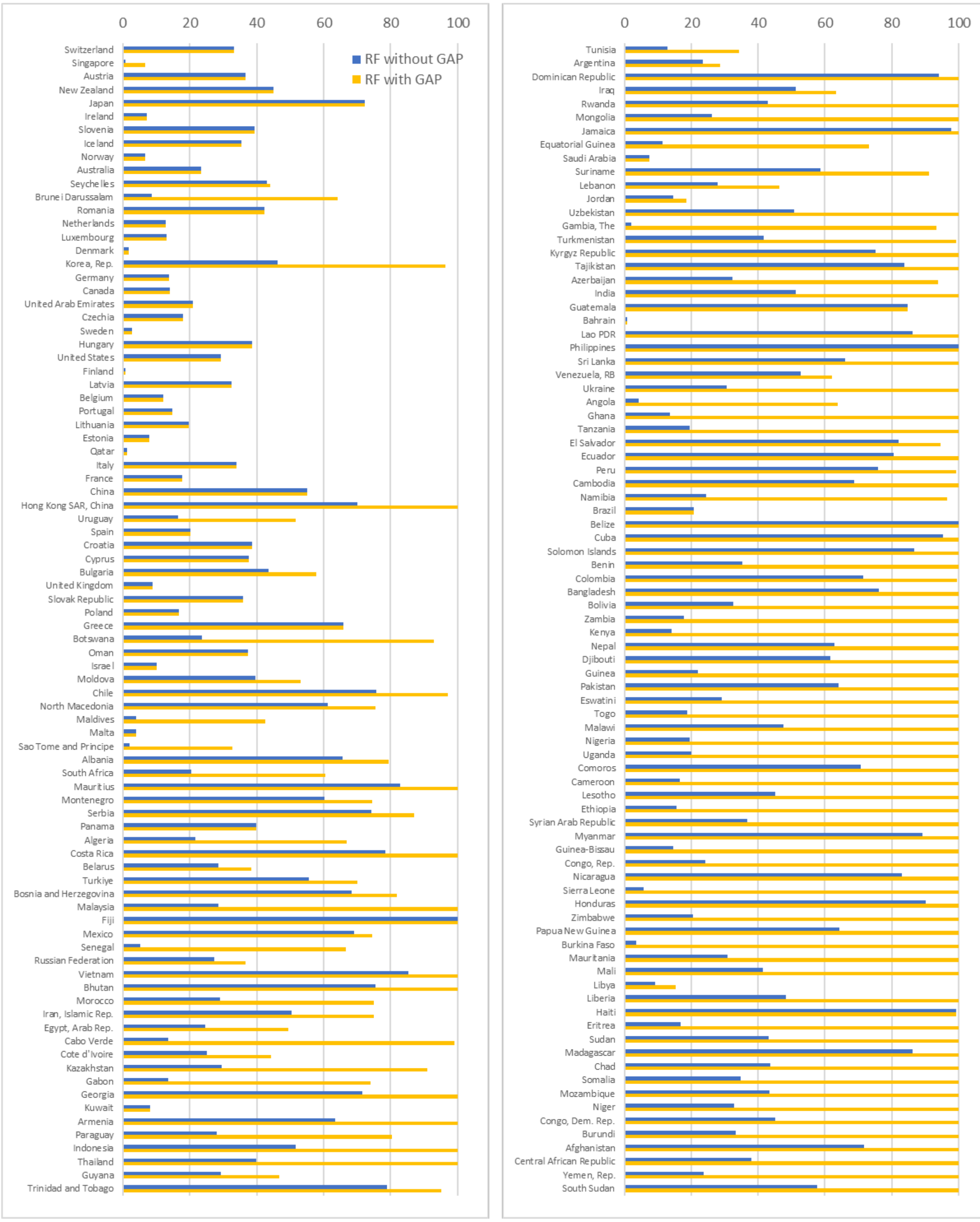

Figure 7. Alteration in Risk Metrics Following Consideration of the Infrastructure Gap Factor.

3.4.3 Inherent Resilience

Considering that the GIRI serves as a disaster risk resilience index, it is essential to incorporate metrics that reflect the physical risk. Figure 8 displays curves for Burkina Faso, Honduras, Algeria, Japan, and the United States. The purpose of this figure is to illustrate the concept of inherent or endogenous resilience, wherein a country's assigned value varies based on the level of physical risk it faces.

To demonstrate the impact of physical risk on the GIRI, inherent resilience curves were created for each country. These curves involve adjusting the value of physical risk, ranging from zero to one, while keeping all other GIRI components constant. This process generates GIRI values for each assigned physical risk value, and the curve represents the combination of all these points for a given country. In Figure 8, the blue points correspond to the GIRI values obtained with the current level of physical risk according to the risk model.

The curves reveal that countries experiencing lower physical risk tend to have higher GIRI values, while higher levels of physical risk lead to a decrease in the GIRI. The steepness or flatness of the curve depends on the capacities of each country. For example, Japan demonstrates stronger capacities compared to the United States of America, Honduras, Algeria, and Burkina Faso.

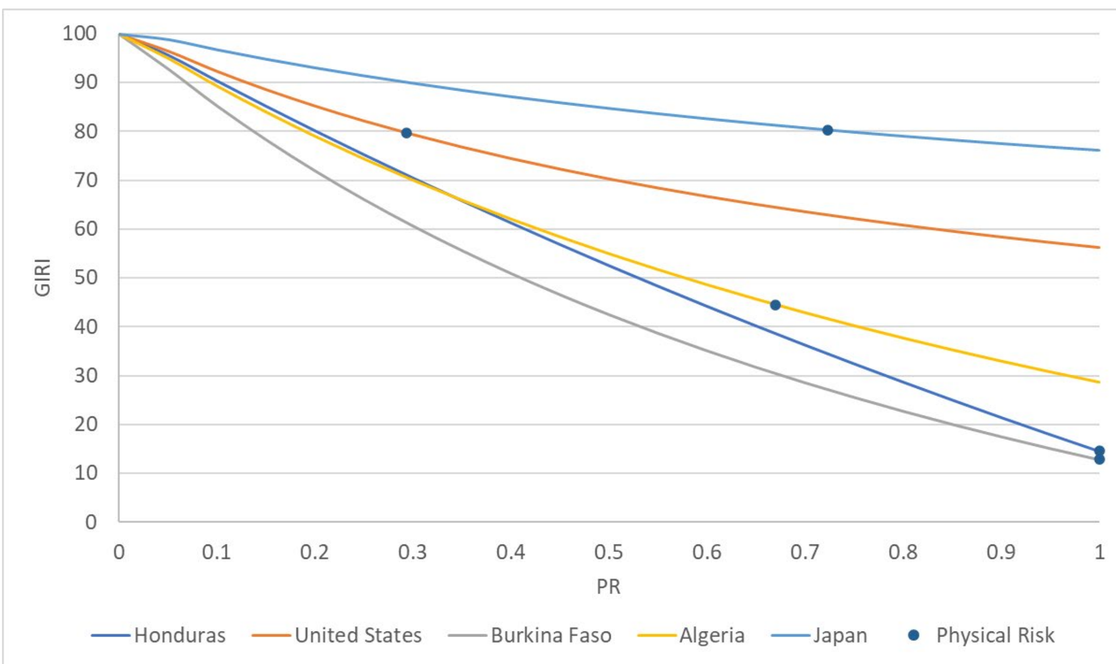

Figure 8. Graphic Representation of Inherent or Endogenous Resilience

The Figure 9 displays the derivative, or rate of change, of the previous resilience performance curves for the same countries. This derivative curve serves as a homomorphism, reflecting the countries' capacities for absorption and recovery. It provides a visual representation of a country's performance in the face of a potential disaster. The y-axis maintains a similarity to performance, while the horizontal axis represents time.

It is important to note that the values resulting from the derivative of inherent resilience do not hold representative significance. However, these figures offer valuable insights into the speed at which a country can restore its infrastructure and services.

In the depicted examples, Japan demonstrates a relatively shorter decline and achieves a faster recovery compared to the other countries presented. Although Honduras experiences a shorter decline than Burkina Faso and Algeria, their capacities enable a more favourable recovery compared to Honduras.

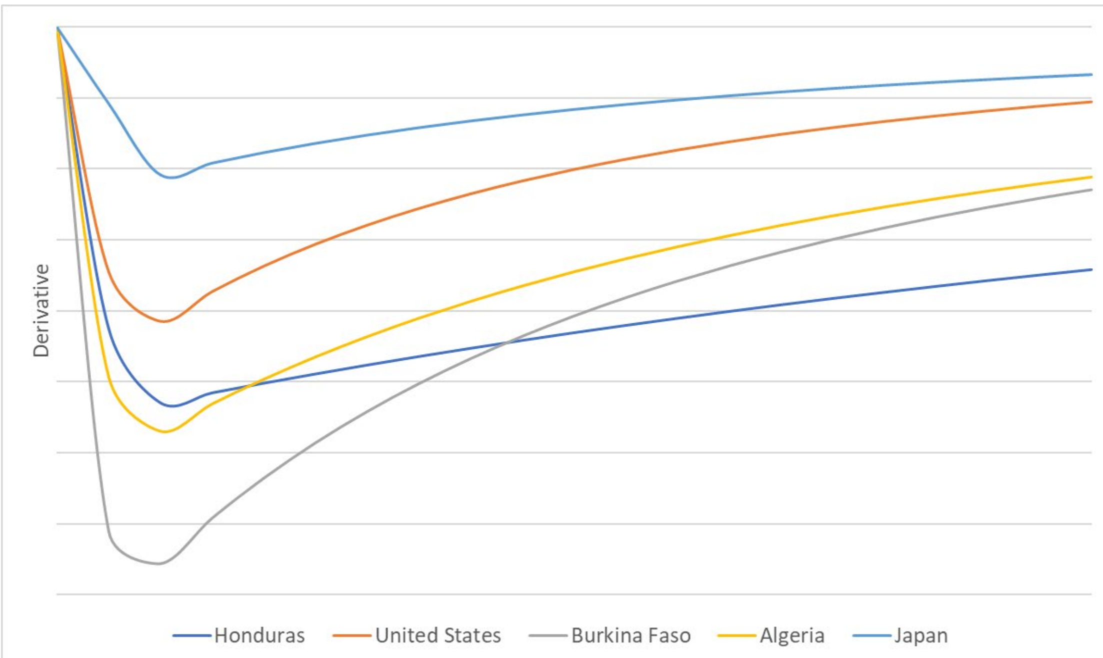

Figure 9. Derivative Curve as a Visual Representation of a Country's Performance in the Face of a Potential Disaster

3.4.4 GIRI Results

The results of the GIRI are valuable for comparing countries, as illustrated in Map 1, Figure 10, and Figure 11. However, it is also important to understand a country’s performance across different capacities and the shape of its resilience performance curve. For instance, countries may have similar GIRI values, but their resilience curves can differ. Figure 12 displays of the profile of India as an example of a summary; including disaggregated information. All country’s profiles are available in a video at: https://youtu.be/VN-GHLH1yas

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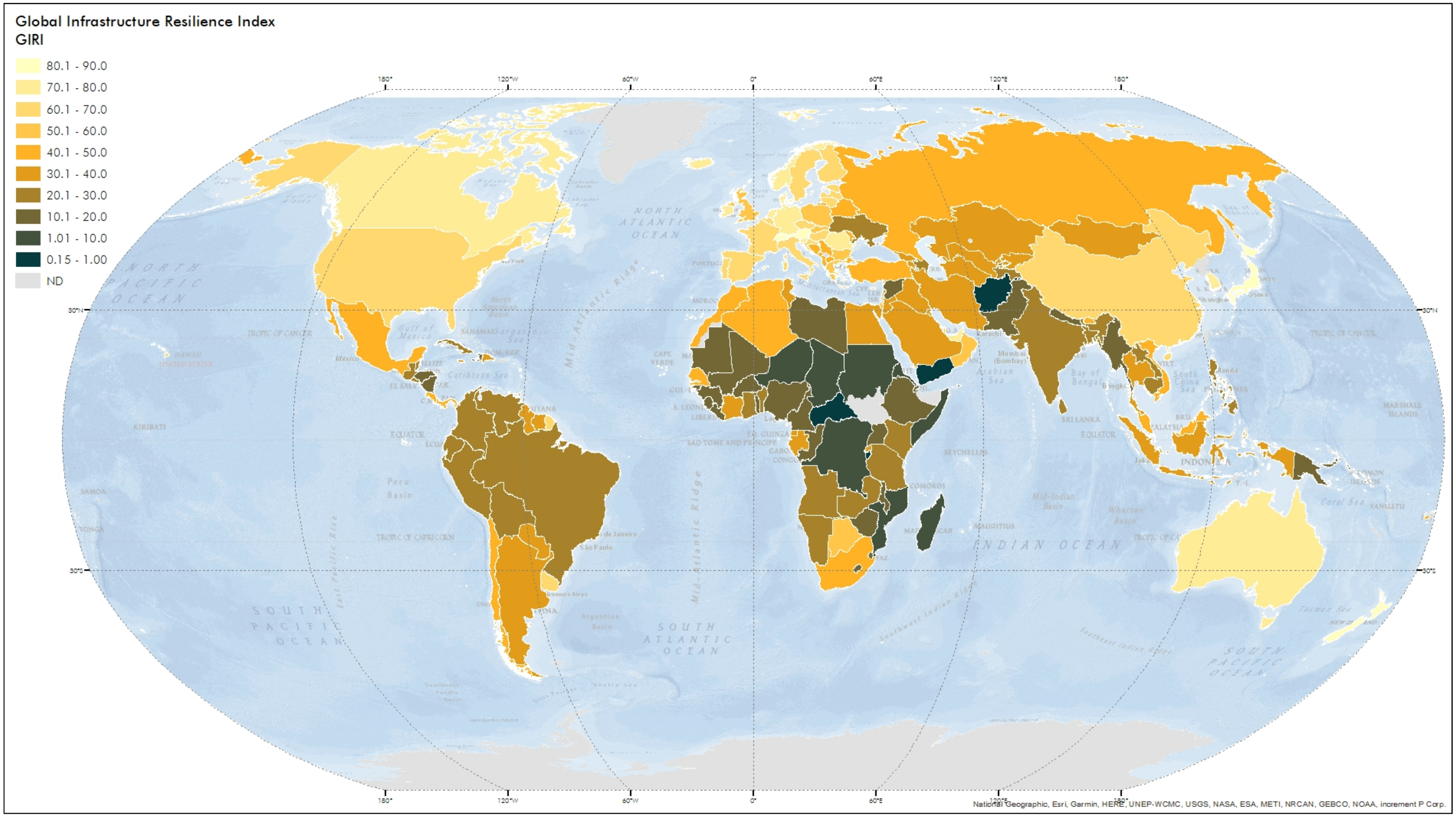

Map 1. Results of the Global Resilience Infrastructure Index, GIRI

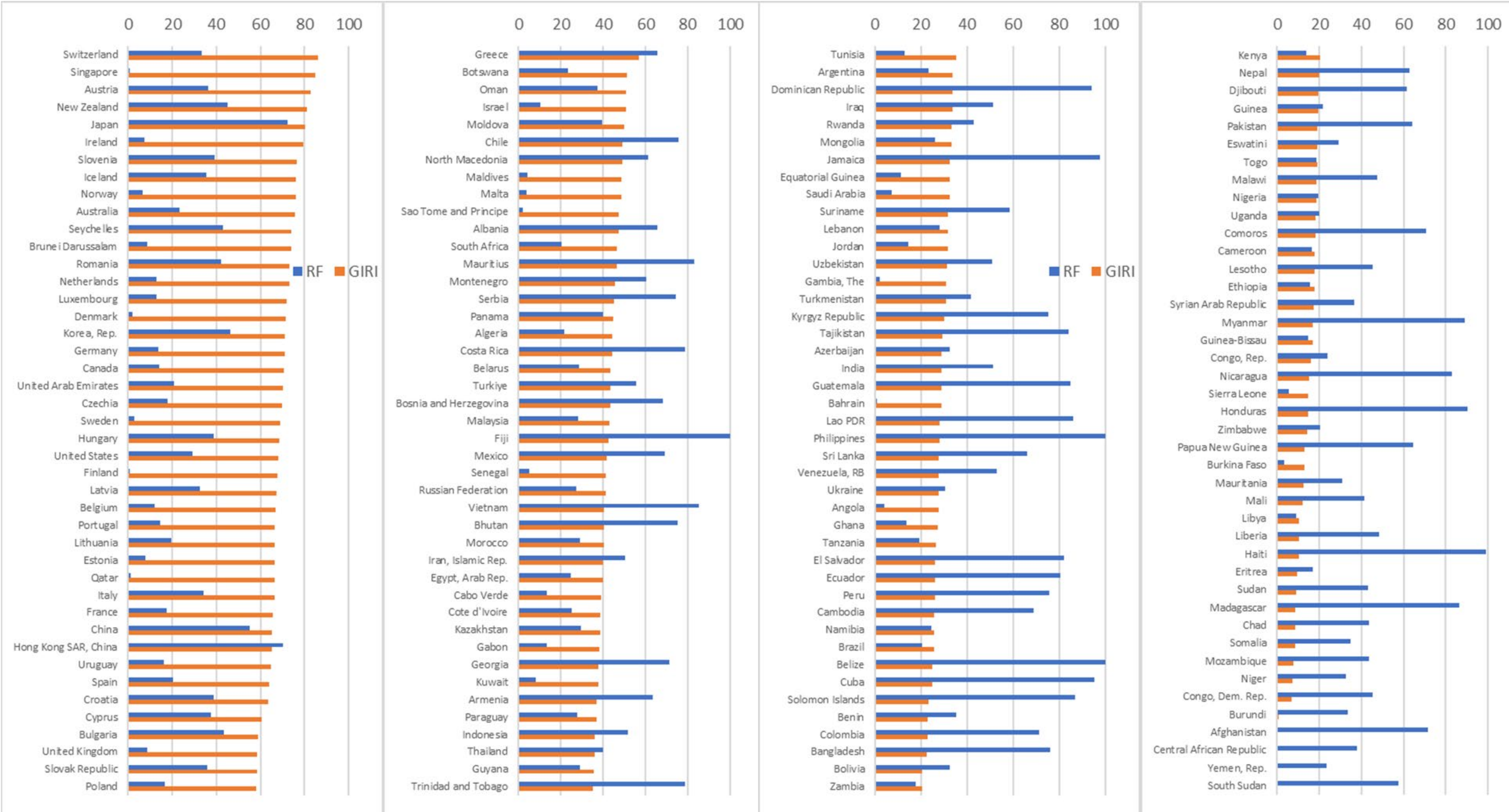

Figure 10. Ranking of the GIRI and the Risk Infrastructure Index (RF) normalized

1	Switzerland	86.1	**44**	Greece	56.7	**87**	Tunisia	35.3	**130**	Kenya	20.3
2	Singapore	85.1	**45**	Botswana	51.1	**88**	Argentina	33.7	**131**	Nepal	19.8
3	Austria	82.8	**46**	Oman	51.0	**89**	Dominican Republic	33.7	**132**	Djibouti	19.6
4	New Zealand	81.2	**47**	Israel	50.9	**90**	Iraq	33.6	**133**	Guinea	19.6
5	Japan	80.3	**48**	Moldova	49.9	**91**	Rwanda	33.5	**134**	Pakistan	19.0
6	Ireland	79.3	**49**	Chile	49.1	**92**	Mongolia	33.4	**135**	Eswatini	19.0
7	Slovenia	76.4	**50**	North Macedonia	49.0	**93**	Jamaica	32.5	**136**	Togo	18.9
8	Iceland	76.1	**51**	Maldives	48.6	**94**	Equatorial Guinea	32.4	**137**	Malawi	18.8
9	Norway	76.1	**52**	Malta	48.5	**95**	Saudi Arabia	32.4	**138**	Nigeria	18.6
10	Australia	75.8	**53**	Sao Tome and Principe	47.3	**96**	Suriname	31.9	**139**	Uganda	18.3
11	Seychelles	74.2	**54**	Albania	47.1	**97**	Lebanon	31.6	**140**	Comoros	18.0
12	Brunei Darussalam	73.8	**55**	South Africa	46.6	**98**	Jordan	31.6	**141**	Cameroon	17.9
13	Romania	73.3	**56**	Mauritius	46.3	**99**	Uzbekistan	31.4	**142**	Lesotho	17.7
14	Netherlands	73.3	**57**	Montenegro	45.8	**100**	Gambia, The	31.0	**143**	Ethiopia	17.7
15	Luxembourg	71.7	**58**	Serbia	45.4	**101**	Turkmenistan	30.8	**144**	Syrian Arab Republic	17.4
16	Denmark	71.3	**59**	Panama	44.9	**102**	Kyrgyz Republic	30.2	**145**	Myanmar	17.1
17	Korea, Rep.	71.3	**60**	Algeria	44.5	**103**	Tajikistan	29.4	**146**	Guinea-Bissau	16.8
18	Germany	71.2	**61**	Costa Rica	44.5	**104**	Azerbaijan	29.0	**147**	Congo, Rep.	16.1
19	Canada	70.6	**62**	Belarus	43.6	**105**	India	28.9	**148**	Nicaragua	15.4
20	United Arab Emirates	70.1	**63**	Turkiye	43.6	**106**	Guatemala	28.8	**149**	Sierra Leone	14.8
21	Czechia	69.8	**64**	Bosnia and Herzegovina	43.4	**107**	Bahrain	28.7	**150**	Honduras	14.5
22	Sweden	69.0	**65**	Malaysia	43.0	**108**	Lao PDR	28.1	**151**	Zimbabwe	14.3
23	Hungary	68.6	**66**	Fiji	42.4	**109**	Philippines	28.1	**152**	Papua New Guinea	13.1
24	United States	68.1	**67**	Mexico	41.9	**110**	Sri Lanka	27.9	**153**	Burkina Faso	12.8
25	Finland	67.9	**68**	Senegal	41.5	**111**	Venezuela, RB	27.8	**154**	Mauritania	12.6
26	Latvia	67.2	**69**	Russian Federation	41.4	**112**	Ukraine	27.8	**155**	Mali	12.0
27	Belgium	67.0	**70**	Vietnam	40.5	**113**	Angola	27.7	**156**	Libya	10.3
28	Portugal	66.7	**71**	Bhutan	40.4	**114**	Ghana	27.1	**157**	Liberia	10.2
29	Lithuania	66.5	**72**	Morocco	40.4	**115**	Tanzania	26.6	**158**	Haiti	10.2
30	Estonia	66.4	**73**	Iran, Islamic Rep.	39.9	**116**	El Salvador	26.2	**159**	Eritrea	9.6
31	Qatar	66.4	**74**	Egypt, Arab Rep.	39.7	**117**	Ecuador	26.0	**160**	Sudan	8.9
32	Italy	66.4	**75**	Cabo Verde	39.1	**118**	Peru	26.0	**161**	Madagascar	8.5
33	France	65.8	**76**	Cote d'Ivoire	38.7	**119**	Cambodia	25.7	**162**	Chad	8.5
34	China	65.2	**77**	Kazakhstan	38.6	**120**	Namibia	25.6	**163**	Somalia	8.4
35	Hong Kong SAR, China	65.1	**78**	Gabon	38.4	**121**	Brazil	25.6	**164**	Mozambique	7.6
36	Uruguay	64.8	**79**	Georgia	37.7	**122**	Belize	24.8	**165**	Niger	7.3
37	Spain	64.0	**80**	Kuwait	37.6	**123**	Cuba	24.8	**166**	Congo, Dem. Rep.	7.0
38	Croatia	63.5	**81**	Armenia	37.0	**124**	Solomon Islands	23.2	**167**	Burundi	3.6
39	Cyprus	60.7	**82**	Paraguay	36.8	**125**	Benin	22.9	**168**	Afghanistan	2.4
40	Bulgaria	58.9	**83**	Indonesia	36.0	**126**	Colombia	22.7	**169**	Central African Republic	1.3
41	United Kingdom	58.6	**84**	Thailand	35.8	**127**	Bangladesh	22.5	**170**	Yemen, Rep.	0.8
42	Slovak Republic	58.4	**85**	Guyana	35.7	**128**	Bolivia	20.6	**171**	South Sudan	0.2
43	Poland	58.2	**86**	Trinidad and Tobago	35.4	**129**	Zambia	20.5			

Figure 10. Results of the Global Resilience Infrastructure Index, GIRI

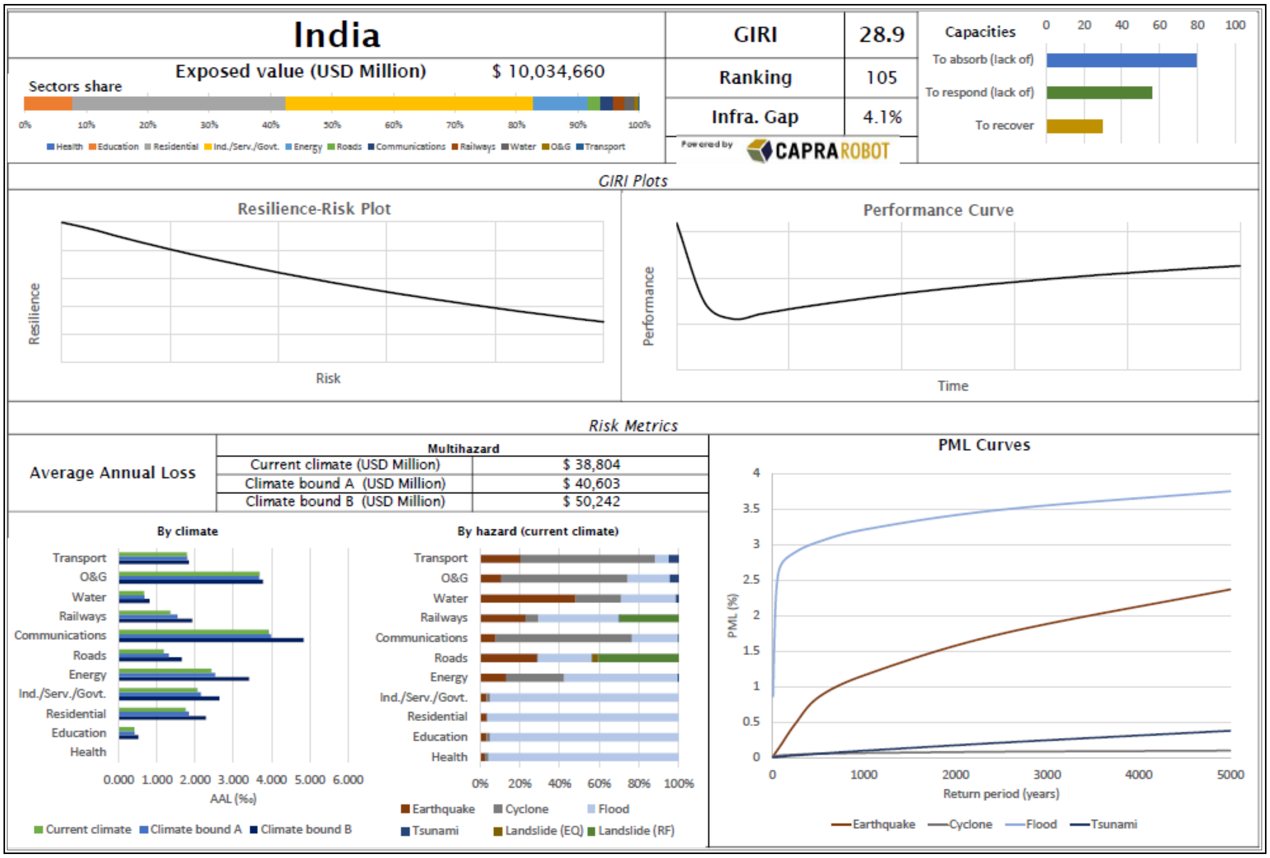

Figure 11. GIRI Profile of India

Infrastructure resilience today is the outcome of the past decisions and actions. However, resilience can be enhanced, through appropriate investments improving infrastructure robustness, flexibility, redundancy and overall quality, including through enhanced design standards, increased investment in operations and maintenance. Modifying the underlying factors that reflect absorptive, responsive, and restorative capabilities will improve adaptability and transformability. It is important to consider resilience as an attribute of performance rather than a static state of a system. The former approach creates incentives for action, whereas the latter may result in inertia and inaction.

The GIRI composite indicator can be utilized to monitor changes in vulnerability and capacities over time, and it can be disaggregated into risk indicators and individual capability indicators. Viewing resilience as a performance characteristic enhances our understanding of the dynamics of change within each country. A similar approach can be implemented at the sub-national level to track infrastructure resilience using a localized GIRI, which incorporates indicators and surveys to directly capture and measure risk and the capabilities of isolated and systemic infrastructures.

The resulting diagrams shall be the tool to measure resilience in each country based on transformed and commensurable indicators associated to each specific absorptive, responsive, and restorative/adaptive capabilities. A world map can be made as the outcome of the resilience ranking of the countries. In summary, all these issues can be reflected from existing indicators issued for all countries providing an operational picture of the abovementioned capacities.

The GIRI can be used to monitor how capacities change over time, which in turn can be disaggregated by the indicators that compose each capacity. Understanding resilience as a performance characteristic improves understanding of the dynamics of change in each country.

The three aspects considered in the GIRI: qualities, capacities, and indicators (physical dimension and contextual dimension) allow identifying in one side, whether existing assets are resilient, if they can provide essential services, on the other side, whether the contextual dimension support resilient infrastructure, or whether it is driving systemic risk. Likewise, the disaggregation of the index to the original indicators allows identifying aspects such as redundancy of systems (i.e., 2G, 3G and 4G network coverage), quality of systems (i.e., Infrastructure quality), systems technology (i.e., technology achievement index), sustainable and fiscal resilience by investing in design, maintenance, implementation, rapid recoverability, among others (i.e., government effectiveness, control of corruption, global peace index), that can reflect the concept of infrastructure for resilience, through providing essential services (service resilience), supporting social and economic development.

An overall risk and resilience landscape will be useful for comparisons and rankings. From the global scale to the local scale, the same approach can be used at any resolution level. After this evaluation at the global level, the countries may carry out their assessments with higher resolution at the sub-national and local levels.

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Annex A. Probabilistic Risk Metrics to Represent the Physical Risk in the GIRI

The frequency of catastrophic events is particularly low and variable according to the type of event, therefore the historical information is generally very limited. The short history of disaster records makes it rather evident that the 'worst-case' scenario is improbable to have occurred yet. Therefore, large losses are rare, and it is difficult to estimate, in statistic terms exceedance rates for them. Their probabilities require considerable judgment (Apostolakis, 1990). In this sense, quantifying physical risk does not mean knowing risk precisely but defining the relevant uncertainties. Analytical approaches can fully represent the physical risk problem by rationally incorporating and propagating the inherent uncertainty in the occurrence of loss and impact. Probabilistic Risk Assessment (PRA), which all catastrophe models implement, is the most appropriate tool for this. As the occurrence of hazardous events cannot be predicted, physical risk models use sets of events to represent all possible ways in which the hazard phenomenon may realize in the area under analysis in terms of both, recurrence (frequency) and severity. Another piece to compute risk is the loss probability distribution as a function of the hazard intensity to represent the vulnerability of the exposed elements. Event-based PRA has been extensively applied to different hazards at different scales (e.g., Grossi & Kunreuther, 2005; Jenkins et al., 2012; Cardona et al., 2014; Niño et al., 2014; Salgado-Gálvez et al., 2014, 2015, 2017; Wong, 2014; Jaimes et al., 2015; Quijano et al., 2015; Bernal et al., 2017;). Hazard, exposure, and vulnerability are the main components of PRA, and can be defined as follows:

- Hazard model: Consists of a set of events (hazard specific), which should exhaustively represent the hazard. Each event contains the frequency of occurrence and the distribution of spatial parameters to characterize the intensity as a random variable.
- Exposure model: Contains characteristics (metada) of each exposed element such as geographical location, replacement value, and building class. Depending on the resolution of the model, it might contain more detailed information on the exposed assets; and
- Vulnerability model: Describes the vulnerability functions for each hazard type and building class. Vulnerability functions characterize the structural performance as a function of hazard intensities. Equivalently, these functions represent the probability distribution of the loss as a function of hazard intensity.

The probabilistic risk assessment quantifies potential losses resulting from a given event, as shown in Figure A. 1.

Physical risk is usually measured by means of the expected number of events per unit time - loss exceedance rate, $\nu(p)$ – that will generate losses equal or larger than p. The total probability theorem is used to compute $\nu(p)$:

$$\nu(p) = \sum_{j=1}^{Events} Pr(P > p|Event_{\,i}) \cdot F_A(Event_{\,i}) \qquad \text{Equation A. 1}$$

where $Pr\ (P>p|Event\ i)$ is the probability of exceedance of the loss p given the occurrence of the event i, and $F_A\ (Event\ i)$ is the annual occurrence frequency of event i. Figure A. 2 shows a flowchart of the risk assessment process (Esteva, 1967; Cornell, 1968; Cardona, 1986; Ordaz, 2000; Grossi & Kunreuther, 2005; Bernal et al., 2019):

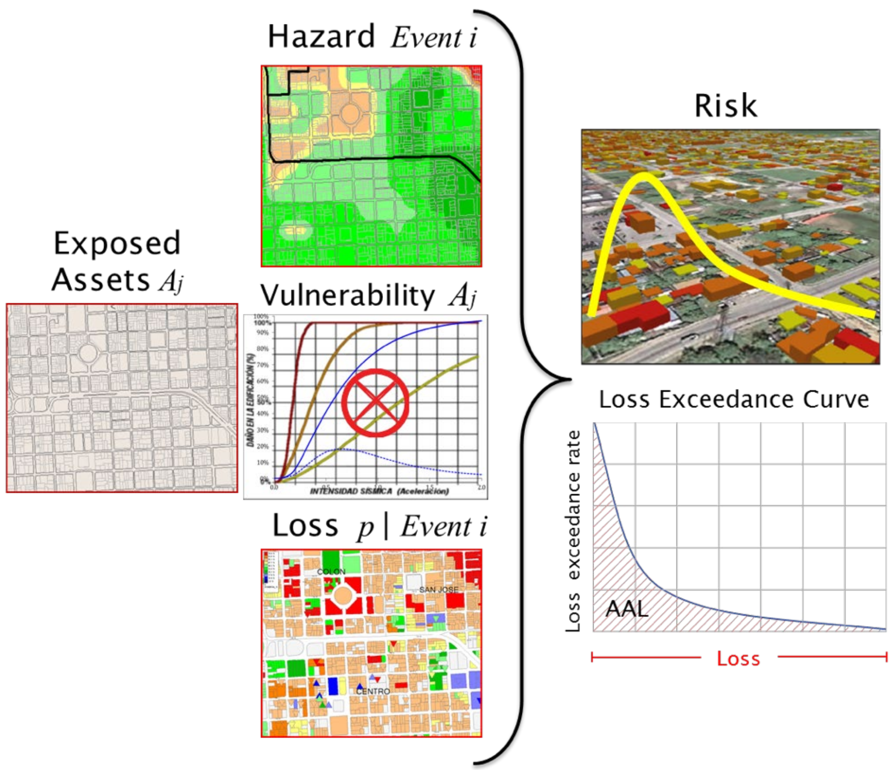


Figure A. 1. Probabilistic Risk Assessment Modeling Scheme.

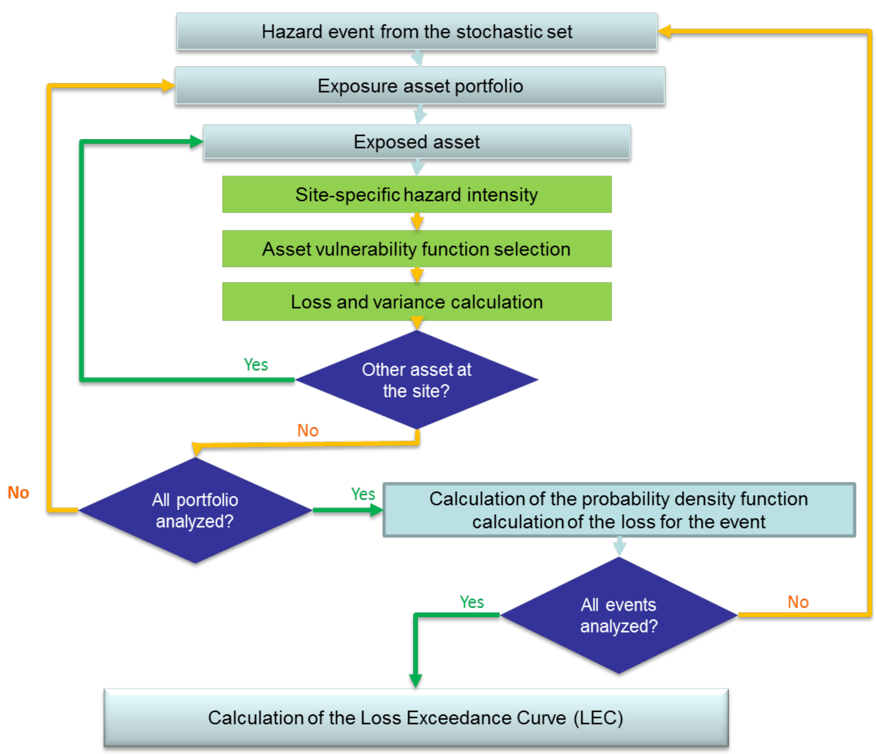


Figure A. 2. Flowchart of probabilistic risk assessment process.

The main risk metric from a fully probabilistic risk assessment is the Loss Exceedance Curve (LEC), which is the most robust tool for representing catastrophe risk (e.g., Cardona, 1986; Ordaz, 2000; Grossi & Kunreuther, 2005; Marulanda, 2013). The LEC provides an exhaustive probability quantification of the risk problem. It is not possible to know the exact losses of a future disaster, however, with a LEC, it is possible to know the exceedance probability of any loss amount within any time frame. This information can support decision-making processes for risk reduction. Diverse risk metrics derive from the LEC such as the Average Annual Loss (AAL) and the Probable Maximum Loss (PML). The AAL or the pure risk premium is a compact metric with low sensitivity to uncertainty that condenses in one number the full losses occurrence process. It expresses the expected (average) loss per year considering all the events that could occur over a long timeframe, including large losses over long return periods. The AAL is basically the sum of the product, for all the stochastic events considered in the loss model, of the expected losses in a specific event and the annual occurrence probability of that event (Ordaz, 2000):

$$AAL = \sum_{i=1}^{Events} E(p|Event_i)\, F_A(Event_i) \qquad \text{Equation A. 2}$$

where $E(P|Event\ i)$ is the expected loss for the event *i* and F_A (*Event i*) is the annual occurrence frequency of the event *i*. The PML is the maximum expected loss in a set of elements exposed for a given return period (or its inverse, annual exceedance rate). The PML curve is the inverse of the LEC.

For this evaluation, instead of using only indicators from damage scenarios, as in the past, physical risk values will be obtained from the normalization of the AAL, values resulted from the multi-hazard fully probabilistic risk assessment. The AAL is a metric that indicates the amount of funds the government or any other responsible entity would have to set aside, annually, to cover for all the potential future damage and losses. This probabilistic metric aims at compressing risk in a single number, and it is the most convenient metric for comparison purposes.

For the evaluation of GIRI, the physical risk index R_F will be calculated based on the results of the probabilistic multi-hazard risk assessment. R_F was calculated considering the relative AAL of each hazard included in the evaluation (tropical cyclones – wind and storm surge, hydrological drouths and floods, landslides, earthquake, tsunami,). The AAL is then transformed to values between 0 and 100, where the maximum value corresponds to those AAL equal to or greater than, for example, 10‰[21] (or 1%). The normalization will be made using functions per segment such as the following:

$$R_F = \begin{cases} 2\left(\dfrac{AAL}{AAL_{max}}\right)^2 & for \quad 0 \le AAL \le AAL_{max}/2 \\ 1 - 2\left(\dfrac{AAL}{AAL_{max}}\right)^2 & for \quad AAL_{max}/2 < AAL \le AAL_{max} \end{cases} \qquad \text{Equation A. 3}$$

where AAL_{max} is the AAL maximum value of normalization (10‰). Other options to be considered are values of PML or the *rate-on-line* for an excess of loss, XL, reference.

[21] 10‰ means a loss of USD 10 per thousand (USD 1.000) of the exposed value.

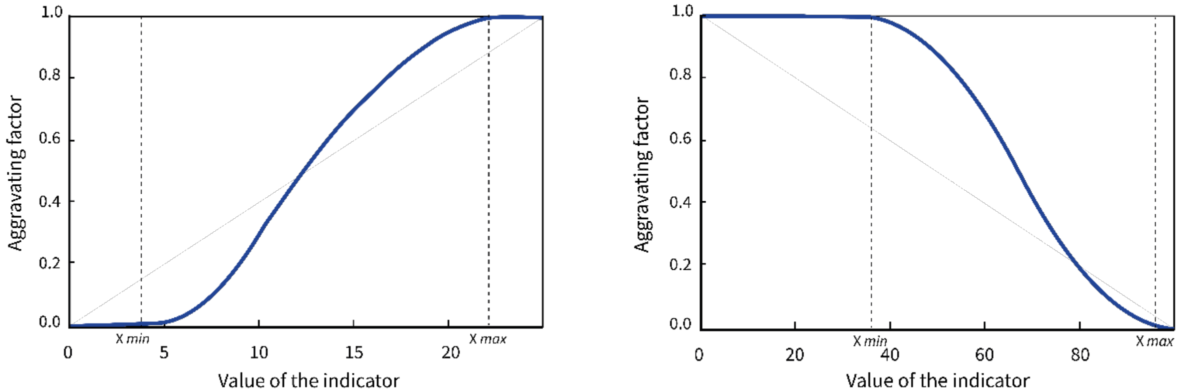
Annex B. Standardization of Absorbing, Responding, and Restoring Capacity Indicators

Regarding holistic approach to total risk, underlying risk drivers that amplify physical risk are incorporated in an aggravating coefficient, *F*, used to aggravate physical risk. This coefficient combines various aspects of society measured by indicators. These indicators have been carefully selected based on expert judgment, seeking to meet the following basic characteristics: i) robust indicators published by national sources or international agencies of broad recognition; ii) available for all (or the majority of) the territorial unities under scrutiny; iii) provide direct information about or are directly related to the contextual conditions. The aggravating coefficient *F* is calculated as the weighted sum of the aggravating factors by their associated weights of each factor. It is assumed that the weight of each factor is the same. In this case, a set of descriptors will be used to capture the quality of infrastructure, the social fragility conditions, and the lack of governance. As expected, these indicators are generated using various techniques, with different units of measurement.

Each indicator has a greater or lesser degree of association with risk -as the inverse of the capacity to absorb- and with responsiveness and restorative capacities, as derived from the context, to provide a complete notion of the resilience, depending on the values they take in each country or territorial unit. In other words, the indicators are generally not commensurable as they are not expressed in equal units and are not associated with a unique quantitative scale. Therefore, a process of standardization is required to operate mathematically with the indicators and obtain consistent results. This process is made by using transformation functions.

The transformation functions can be understood as resilience probability distribution functions or as the membership functions of the linguistic benchmarking of high resilience or high anticipative/absorptive, responsive, restorative, or recovery/adaptive capabilities. The degree of association to context-derived resilience can be expressed in linguistic terms, as is commonly done in expert-based assessment processes. In other words, an indicator of, for example, deprivation has an increased association with the aggravation of physical risk (i.e., the higher the level of deprivation, the greater the aggravation). It is also possible to consider a scale allowing the value of the indicator to be associated with a level of aggravation; for example: ‘low’, ‘medium’, or ‘high’. However, the linguistic qualification implies a degree of association that may be related to the probability of an aggravating level for a certain range of the indicator’s value. Thus, the normalization process of the indicators seeks to establish the probability that a value of an indicator is associated with a significant increase of any of the considered capabilities.

Carreño (2006) defined a general form for the transformation of indicators by means of S functions (for increasing association indicators) or Z functions (for decreasing association indicators). Indicators are transformed independently using these types of functions, according to the range of values to be covered and the relevance of the indicator to reflect risk amplification and resilience capacities, as appropriate. Figure B. 1 presents an example of functions S and Z.



In the increasing function S, a high value of the indicators results in a greater contribution to the factor measure.

In the inverse and decreasing function Z, a high value of the indicator means a lesser influence on the factor measure.

Figure B. 1. Example of Transformation Functions S and Z.

The values on the abscissa correspond to the gross values of the indicators, while values on the ordinates correspond to the normalized value. A membership value of 0.0 means no membership (or no contribution to the aggravating coefficient or capability dimension), while 1.0 means full membership (or full contribution to the aggravating coefficient or capability). X_{min} and X_{max} values are defined accordingly to the range of values covered in the territory. While the transformation process makes the indicators commensurable and establishes their association with the aggravation or capacity, it is possible that some of these indicators, or several, may have greater relative importance in explaining the contextual conditions that lead to disaster risk (or other resilience component). For this reason, a collection of weights is established, which directly affects each indicator and measures their relative degree of importance within the context under assessment. However, due to the wide scope of this assessment, where a consensus process is not feasible, to avoid discussions about the relevance of each aspect, and considering the robustness and sensitivity analysis performed by Marulanda et al., (2009), relative weights that associate the importance of each of the factors on the index calculation are defined in this specific evaluation as equal, that is, it is assigned the same importance or contribution to each of the indicators intending to characterize the socio-economic dynamics of the community.

From the context-derived risk and resilience assessment, this approach allows the disaggregation of the results to determine the degree of the relative weight of the different indicators and the specific aspects they reflect, thus, identifying the areas requiring more attention when addressing risk management and adaptation strategies. The analysis of these indicators and the aspects they reflect, make it possible to focus efforts on non-physical aspects of risk and resilience.

This kind of evaluation must periodically update to evaluate the changes in risk and resilience and development through time. The results obtained also allow measuring the progress towards reaching the goals established in the Sendai Framework for Disaster Risk Reduction 2015-2030, and the Sustainable Development Goals SDG, without waiting for disasters to occur. It is therefore possible to measure progress by identifying and reducing future negative effects and impacts of hazardous events in vulnerable human settings which may even allow avoiding the occurrence of disasters (Muir-Wood, 2016).

Lastly, the development of indexes of multi-hazard risk and resilience using a holistic, multi-sectoral, and interdisciplinary approach is a task to achieve in each country. This effort of risk science is a key step to provide the risk and resilience landscape that is emerging at different scales and sectors. Risk and resilience are complex and systemic, and it is necessary to consider their distinct dimensions, components, and interdependencies. This comprehensive perspective of risk and resilience is especially relevant for risk-informed decision-making and the way for integrated risk management and transformative adaptation, identifying and tackling the underlying causes and drivers of risk, addressing the factors exacerbating risk and that reflect resilience, with prominence given to the issues of justice and equity.

Annex C. Relevance of the Indicators

CAPACITY TO ABSORB				
Indicator	**Values**	**Description**	**Source**	**Relevance**
Infrastructure Quality	0-2	*Component of the Global Resilience Index* The quality and extension of transport infrastructure (road, rail, water and air) and utility infrastructure	FM Global	Risk identification and measurement drives better decision making at all levels for an effective implementation of risk reduction and mitigation policies.
Building Quality Control Index	0-15	The BQCI is the sum of the following six indices: i) Quality of building regulations; ii) Quality control before construction; iii) Quality control during construction; iv) Quality control after construction; v) Liability and insurance regimes; vi) Professional certifications	World Bank	Good construction regulation matters for public safety since sound regulation of construction helps protect the public from faulty building practices. Efficient construction permitting and inspection systems can indeed strengthen property rights and contribute to the process of capital formation. If procedures are too complicated or too costly, builders are more likely to proceed without a permit, especially in developing economies. And because the construction permitting process generally involves licensing requirements from several different agencies, those seeking permits are exposed to different bureaucracies, which creates opportunities for rent-seeking. Overly complicated or costly construction rules can also increase opportunities for corruption.
Ecosystem Vitality		The Ecosystem Vitality policy objective measures how well countries are preserving, protecting, and enhancing ecosystems and the services they provide.	EPI – Yale University	Healthy ecosystems can lead to more sustainable growth of assets and income, economic development, and well-being of people. Ecosystem preservation and restoration can contribute to resilience to climate change and to climate change mitigation. In turn, environmental degradation is a major driver of disaster risk. Low quality and quantity of ecosystem services exacerbates climate change.
GINI Index	0-1	The GINI index represents the income inequality or the wealth inequality or the consumption inequality within a nation or a social group	World Bank	Social inequalities can increase vulnerability due to the lack of capacity to cope with an impact of an event. Disasters are a bigger burden in more unequal countries given the lack of affordability to implement preventive

				measures, or limited access to resources to ensure resilience to events. More equal societies are also more resilient. Flatter hierarchies lead to higher cooperation among individuals (Germano and Demetrius, 2014)
Housing Deprivation	0-100	*Indicator of shelter of the Multidimensional poverty index* The percentage of households deprived in the quality of roofing, walls, or flooring; if the household has no walls or if the wall is made of natural, rudimentary, or other unidentified materials, if the household has no roof or if the roof is made of natural, rudimentary or other unidentified materials, or if there is a natural floor.	Oxford Poverty and Human Development Indicators	The capacity of absorbing the impact of disasters is undermined by the persistence of inequality at its different dimensions. This is an indicator of a comparative unfavorable situation that reflects the level of inequality of a country and the government capacity to provide proper living conditions for the population in terms of safe and affordable housing (SDG 11). Thus, higher rates of population living in housing deprivation reflect a weak economy and therefore a low investment capacity of the State to strengthen key sectors for building resilient communities. This indicator is related with the capacity feature of resilience, defined as the ability to withstand unforeseen events, and absorb its impacts.
Global Peace Index	1-5	The GPI measures a country's level of Negative Peace using three domains of peacefulness. The first domain, Ongoing Domestic and International Conflict, uses six statistical indicators to investigate the extent to which countries are involved in internal and external conflicts, as well as their role and duration of involvement in conflicts. The second domain evaluates the level of harmony or discord within a nation; eleven indicators broadly assess what might be described as Societal Safety and Security. The assertion is that low crime rates, minimal terrorist activity and violent demonstrations, harmonious relations with neighboring countries, a stable political scene and a small proportion of the population being internally displaced or made refugees can	Vision of Humanity	Societies with high Positive Peace have better outcomes on a range of factors that are considered important, such as better per capita growth, better environmental performance, less civil resistance movements or violent political shocks but also better infrastructure to weather the impact from natural disasters.

		be equated with peacefulness. Six further indicators are related to a country's Militarization—reflecting the link between a country's level of military build-up and access to weapons and its level of peacefulness, both domestically and internationally.		

CAPACITY TO RESPOND				
Indicator	**Values**	**Description**	**Source**	**Relevance**
Macroeconomic Stability	0-100	*Component of the prosperity index* Measures how robust an economy is. It is a composite measure based on, (a) GDP per capita growth and (b) Inflation volatility	Legatum Institute	Strong economies are an indicator of high productive and competitive countries. A strong economy means that a government will have more resources at hand when disaster strikes being therefore able to respond in a timely manner without having to incur in excessive debt.
Control of Corruption	0-1	*Component of the World Governance Indicators* Control of corruption captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.	World Bank	Corruption constitutes a heavy burden for the proper allocation of resources for disaster risk management at all levels: risk knowledge, risk reduction and disaster management. Especially in the latter stage, where the financial aid received might be less effective than expected due to corruption, thus weakening the effectiveness of and trust in the government.
2G, 3G and 4G Network Coverage	0-100	*Component of the prosperity index* Assesses the means of communication and how widespread access to communication is	Legatum Institute	Access to communication has an impact on the effective transmission of information which can have a direct impact on how well crisis are managed. Well-managed information reaching many people and agencies can result in more timely response and integrated service when disaster strikes. Better network coverage might also facilitate post-disaster response by providing valuable insights and reports of the damages (e.g., Disaster Maps Product).
Logistics and Performance Index		The LPI consists therefore of both qualitative and quantitative measures and helps build profiles of logistics friendliness for these countries. It measures	World Bank	Emergency response requires proper, structured, standardized, and organized logistics in order to respond efficiently and fast.

		performance along the logistics supply chain within a country.		LPI is considered as a vital element in economy's competitiveness (Arvis et al., 2007). It is related to businesses and gives an understanding on how well countries do in terms of logistics processes, logistics environment and institutions, constraints hindering smooth flow of logistics activities present at ports, borders or inside the country. It is measured in six areas that include 'infrastructure', 'services', 'border procedures and time' and 'supply chain reliability' (World Bank, 2020). Underdevelopment of logistics can result in aggravated trade costs and hinder smooth flow of goods because of impoverished infrastructure, poor transportation facilities and uncontrolled bureaucracy of the state institutions. Underdevelopment of logistics can result in underperforming in emergency response due to the incapacity to handle an event fast and efficiently.
Gross National Savings		The national savings rate measures the amount of income that households, businesses, and governments save. It looks at the difference between the nation's income and consumption and is a gauge of a nation's financial health, as investments are generated through savings.	World Bank	GNS is a gauge of a nation's financial health, as investments are generated through savings. Gross National Savings can serve for both, access to resources in case of emergencies, or as a backup to borrow economic resources to respond to emergencies.
Political Stability	0-1	*Indicator of the Governance Indicators of the World Bank.* Political stability and absence of violence measures perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically motivated violence and terrorism.	World Bank	Political instability and violence may undermine response efforts due to the difficulty to access resources, to the lack of strong institutions, that avoid the rapid and efficient interventions.

CAPACITY TO RESTORE				
Indicator	**Values**	**Description**	**Source**	**Relevance**
Government Effectiveness Index	0-1	*Component of the World Governance Indicators* Government effectiveness captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. Government effectiveness captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.	World Bank	This index reflects the capacity of a government to effectively develop national action plans, policies and implementation measures and turn them into actions addressed to provide overall well-being to the population, through the provision of public goods, social security, etc., In sum, of providing the conditions that allow for a robust recovery.
Research and Development	0-100	*Component of the Global Innovation Index* A composite measure based on, (a) Researchers, full-time equivalent (per million population), (b) Gross expenditure on R&D (% GDP), (c) Average expenditure of a country's top 3 global companies (m USD), (d) QS university ranking	World Intellectual Property Organization	According to the OECD R&D intensity is one of several indicators used to measure progress toward achieving the UN Sustainable Development Goal (SDG) 9 on innovation. SGD Goal 9 seeks to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. Statistics for government R&D budgets also provide insights into the socioeconomic objectives that governments pursue, thereby helping to assess the directionality of public R&D policies.

Access to Quality Education	0-1	*Component of the prosperity index* A composite measure, made from the score given to the top-1000 universities in the QS World University Rankings and TES Higher Education World University Rankings, normalized by number of higher education institutions in the country. QS World University Rankings and TES University Rankings A measure of the degree to which high quality basic education is guaranteed to all, being sufficient to enable them to exercise their basic rights as adult citizens.	Legatum Institute	Access to quality education leads to a country with a higher productivity and therefore a country with a stronger economy. Without education no progress is sustainable, education is an essential means for raising awareness towards risks and the importance of holding the government accountable. Furthermore, access to quality education ensures the presence of high qualified professionals that will work towards a robust and quick recovery.
Technology Achievement Index	0-1	A composite index that reflects countries' ability to create and diffuse technology as well as building human skills. It evaluates the technological performance of countries, classifies countries according to their technological achievements.	Desai et al. 2022, UNDP	Countries that can adapt to the pace of technological developments, follow and use this speed have a stronger economy and obtain a significant competitive advantage in the global arena. Therefore, the countries make various regulations to increase the technological achievements, access to the global technologies, adapt to the rapid technological transformation and organize their sub-structures according to these technologies (Incekara, A., T. Guz and G. Sengun, (2017)). Finally, the availability of such technologies will likely speed up the recovery and building back better processes.
Human Development Index		The Human Development Index is a statistic composite index of life expectancy, education, and per capita income indicators,	UNDP	Many of the main objectives of human development – such as poverty reduction, quality education, affordable housing, social equity and equality, food security – reduce vulnerabilities of individuals, groups, and communities to disasters (Hallegatte et al., 2020, Lewis, 2012, UNDP, 2020, UNDP, 2004). High HDI can reflect better levels of education, which is important for developing cognitive and critical skills and scientific knowledge to be better informed. Better health systems that allow a continuous and more sustainable

				provisions for ensuring a better recovery. Good income levels can reflect availability of savings, access to credits, insurance, that will help to recover faster and more efficiently.
Economic Complexity Index	(-2) - 2	The Economic Complexity Index, or ECI, is a measure of an economy's capacity which can be inferred from data connecting locations to the activities that are present in them. The Economic Complexity Index has been shown to predict important macroeconomic outcomes, including a country's level of income, economic growth, income inequality, and greenhouse gas emissions.	Observatory of Economic Complexity	This index reflects the overall state of the economy of a country and therefore its capacity to successfully cope with the negative impact of hazard events.