Chapter 15
Unveiling the Latent Disasters from a Holistic and Probabilistic View: Development of a National Risk Atlas

Paula Marulanda-Fraume, Omar-Darío Cardona, Mabel-Cristina Marulanda, and Martha-Liliana Carreño

Abstract 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 socio-economic and environmental factors, non-hazard-dependent. This approach seeks to capture how these latter 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. This article presents the results of the holistic evaluation obtained at the subnational level in Colombia in the framework of the Risk Atlas of Colombia of the National Unit for Disaster Risk Management (UNGRD, its Spanish acronym). The evaluation was performed using the probabilistic physical risk results derived from a multi-hazard risk assessment, with 16 socio-economic indicators available for the 1123 municipalities of Colombia. These results are relevant for comparison purposes and are also useful to identify the risk drivers associated not only with the current risk conditions but also those shaping future risk.

P. Marulanda-Fraume
INGENIAR: Risk Intelligence, Bogotá, Colombia
e-mail: paula.marulanda@ingeniar-risk.com

O.-D. Cardona (✉)
INGENIAR: Risk Intelligence, Bogotá, Colombia

Instituto de Estudios Ambientales, Universidad Nacional de Colombia, Manizales, Colombia
e-mail: odcardonaa@unal.edu.co

M.-C. Marulanda
Centro de Investigación para la Gestión Integrada del Riesgo de Desastres (CIGIDEN), Santiago de Chile, Chile

BCM/IEM, Rabdan Academy, Abu Dhabi, United Arab Emirates

M.-L. Carreño
Centre Internacional de Mètodes Numèrics a L'Enginyeria (CIMNE), Barcelona, Spain

1   Introduction

From the perspective of disasters, risk has been measured to address it as the possible economic, social, and environmental consequences derived from a natural or anthropic event. Disaster risk is not only linked to the occurrence of natural events but also – and mainly – to the prevalent conditions of vulnerability favoring the happening of disasters. However, very few analyses address risk in a comprehensive manner, and in most cases, their approach is mainly oriented toward a social characterization of vulnerability, treating it as equivalent to risk and not as a condition of susceptibility, leaving aside the fact that potential physical damage is essential when it comes to estimating risk. Therefore, the likelihood of occurrence of a negative impact, derived from a natural or anthropic event, implies the convergence of physical, natural, social, economic, and political factors that require a holistic approach where appropriate involvement is ensured for every aspect of the configuration of 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 number of conditions that, combined with a natural event, result in disaster (Oliver-Smith, 2004).

Therefore, risk as currently configured is the result of a social process of many years, which determines 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 socio-economic 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 well-being in a geographic area contribute to increasing risk (Ambraseys, 2010).

Although the public interest in risk assessment has increased in the last decades and it has been accepted that losses resulting from hazardous events are avoidable, up to at least some degree of human control, and therefore actions can and should be taken to prevent and reduce risk, insufficient disaster risk understanding can lead to its underestimation and therefore to a lack of actions addressed to the reduction of their impact (Jamali et al., 2022). As highlighted by the UNDP Global Report (UNDP, 2004) "Disaster risk is not inevitable, but it can be managed and reduced through appropriate development actions."

One of the main challenges related to risk assessment 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, by offering a simplified representation of a multidimensional concept. They are big pictures that allow an easier interpretation of

complex issues instead of trying to find trends in many separate indicators. Indicators highlight some of the aspects of risk and contribute to the formulation and analysis of public policies and decision-making processes. However, indicators are not aimed at identifying risk management measures, which instead must be identified by integrated models and comprehensive risk analysis. Risk assessments help to facilitate risk communication, revealing the importance of introducing them in development plans.

The concept of risk is linked to decision-making; this means that risk must be measured to make decisions about the feasibility or convenience of carrying out actions to prevent it or reduce it. What is not measured cannot be managed, and therefore in defining a robust strategy for risk management, the first step is to be rigorously evaluated. Risk is a crosscutting notion, and as such it must be addressed through a comprehensive and multidisciplinary approach. 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. Based upon this understanding, a holistic approach for risk assessment was carried out at a subnational level in Colombia for its 32 departments and 1123 municipalities, integrating physical risk resulting from a multi-hazard assessment and a set of socio-economic indicators. The results of this evaluation are presented herein.

2 The Holistic Approach

Holistic risk assessment considers, within a single conceptual framework, hazard and vulnerability, both physical, understood as the susceptibility to damage of the exposed elements, and contextual, expressed through a set of socio-economic factors. Figure 15.1 illustrates the conceptual framework applied in this evaluation. Hazards are events of potential occurrence that have a destructive effect on the exposed elements (i.e., exposure), characterized by a physical vulnerability and by contextual conditions amplifying or exacerbating physical damages that can be associated with socio-economic indicators describing lack of resilience and social fragility. The convolution of these aspects derives from the likelihood of impact (risk). 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.

Tackling risk 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 risk, as well as the created hazards (anthropogenic, technological). Likewise, as part of the risk management framework, emergency response and recovery plans based on risk assessments must be defined, allowing for a quick and effective response when a disaster occurs. For management purposes, risk studies support improved decision-making contributing to the effectiveness of risk management by inviting action and
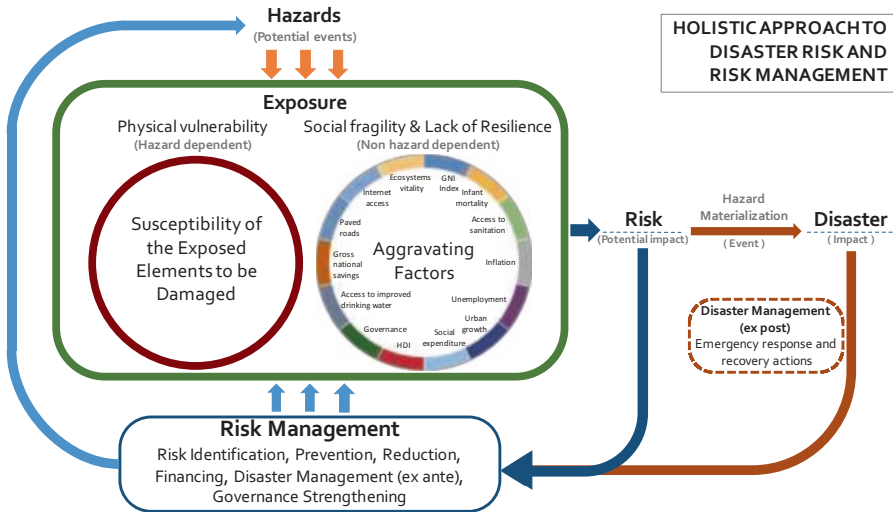
Fig. 15.1 Conceptual framework of the holistic approach to risk assessment and management (Cardona, 2001); used at UNDRR (2017) and UNGRD (2018)

identifying weaknesses of the elements exposed, as well as their evolution over time (Cardona, 2001; Carreño, 2006; Carreño et al., 2007).

Holistic evaluations of risk derived of seismic hazards and vulnerability in urban areas have been performed in recent years for different cities worldwide, Carreño et al. (2007); Birkmann et al. (2013); Marulanda et al. (2013); Jaramillo (2014); Salgado-Gálvez et al. (2016), as well as at country level, Daniell et al. (2010); Burton and Silva (2014); and at global level: UNDRR (2017), proving to be a useful way to assess, compare and communicate risk while promoting effective actions toward the intervention of vulnerability, measured at its different dimensions. This approach has also been integrated into toolkits, guidebooks, and databases for earthquake risk assessment, Burton et al. (2014); Khazai et al. (2015). Most recently, a study based on the conceptual approaches of this methodology was carried out in the USA by FEMA (2020). The results presented in this article are from the first application of this methodology at the departmental and municipal level, for the 32 departments and 1123 municipalities under the framework of the Risk Atlas of Colombia (UNGRD et al., 2018), and considering four different hazards.

The holistic risk 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.

– Socio-economic 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.
– 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, 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 lack of resilience, that is, the incapacity to anticipate, recover, and absorb the impact, which is not dependent on or conditioned by the effects and impacts of the event.

This methodology 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 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 actions and assess the (in)effectiveness of measures taken in the past. This is the first time that a study, following the above mentioned methodology, is conducted considering hazard, exposure, and socio-economic descriptors at the subnational level for a whole country. 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 municipalities promoting effective actions for the intervention of vulnerability conditions measured in their different dimensions.

3   The Risk Assessment Methodology

Under this methodology, total risk R_T is a function correlating the potential physical damage R_F, and the aggravating factor F. R_F is obtained from the vulnerability (physical susceptibility) of the exposed elements to hazards (defined in function of intensity during a specific period). F depends on the social fragilities and the lack of resilience, that is, how prone the system is to suffer damages and losses. 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:

$$R_T = R_F \left(1 + F\right)$$

<div align="right">(15.1)</div>

known in the literature as Moncho's equation, where R_F 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_F is obtained from the 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. Note that there can be no context-derived risk without physical risk (loss, damage, or direct effects), a characteristic that stems from the integral nature of the holistic assessment. Detailed information about this methodology can be found in Carreño (2006), Carreño et al. (2007), Barbat et al. (2011), and Marulanda et al. (2020).

3.1   The Probabilistic Risk Metrics

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 occur 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., 2015; Salgado-Gálvez et al., 2014, 2015, 2017; Wong, 2014; Jaimes et al., 2015; Quijano et al., 2014; 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.

– 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 Fig. 15.2.

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 $\nu(p)$:

$$\nu\left(p\right) = \sum_{j=1}^{\text{Events}} \Pr(P > p | \text{Event}_i) \bullet F_A\left(\text{Event}_i\right) \tag{15.2}$$

where $Pr(P > p|\text{Event } i)$ is the probability of exceedance of the loss p given the occurrence of the event i and $F_A(\text{Event } i)$ is the annual occurrence frequency of event i. Figure 15.3 shows a flowchart of the risk assessment process (Esteva, 1967; Cornell, 1968; Cardona, 1986; Ordaz, 2000; Grossi & Kunreuther, 2005; Bernal et al., 2019).

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 et al., 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 time frame, 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):

$$AAL = \sum_{i=1}^{\text{Events}} E(p | \text{Event}_i) F_A\left(\text{Event}_i\right) \tag{15.3}$$
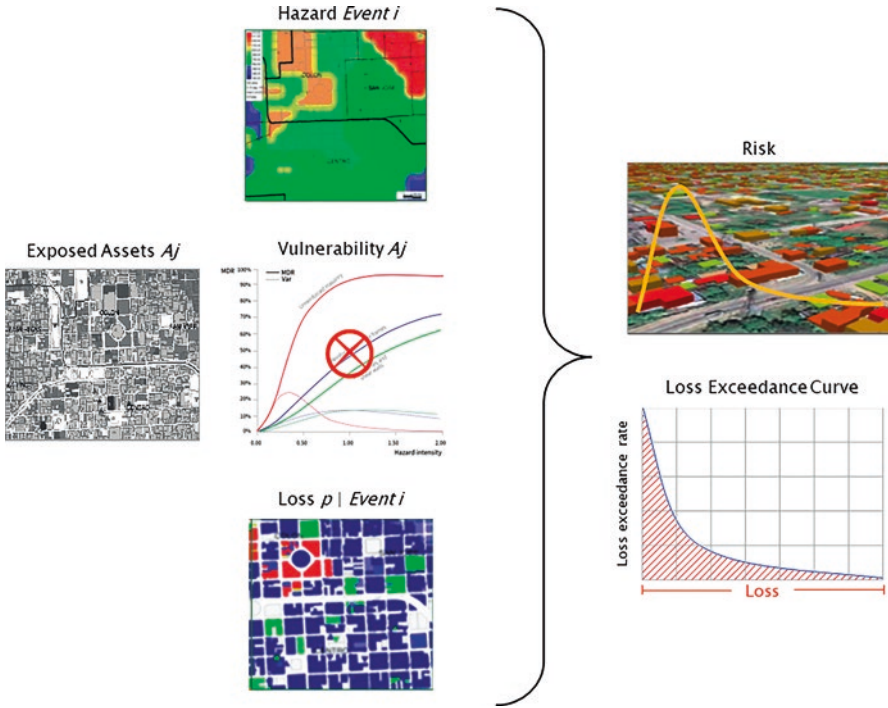
Fig. 15.2 Probabilistic risk assessment modeling scheme

where $E(P|\text{Event } i)$ 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.

3.2 The Expected Losses as Physical Risk Indicators

For this evaluation, instead of using only indicators from damage scenarios, as in the past, physical risk values were 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.

The physical risk index R_F was calculated based on the results of the probabilistic multi-hazard risk assessment considering the relative AAL of each hazard included in the evaluation (earthquake; tsunami; tropical cyclones – wind and storm surge;
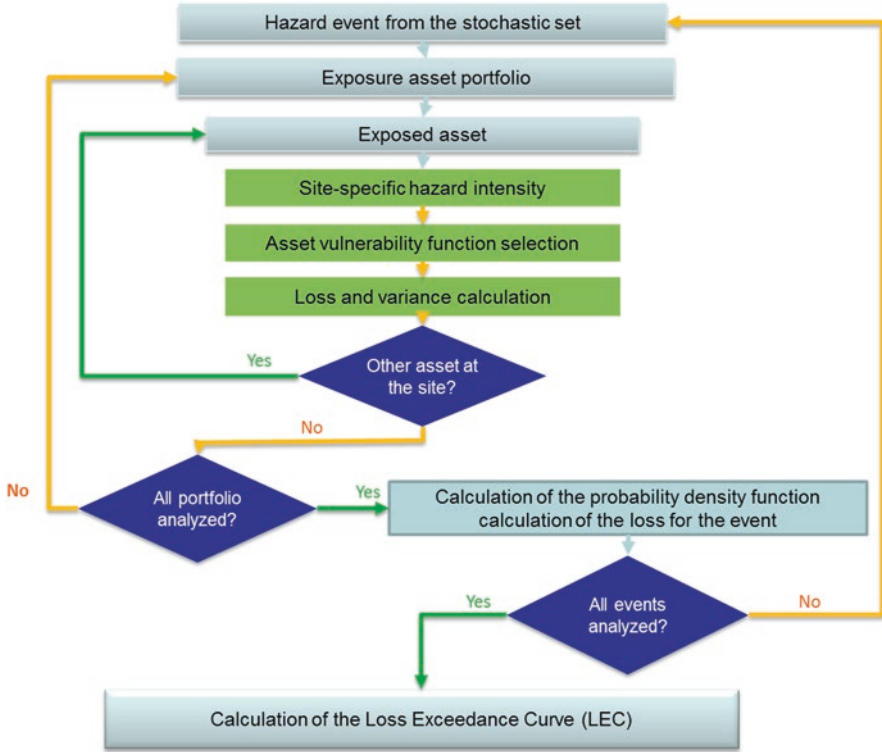
Fig. 15.3 Flowchart of probabilistic risk assessment process

and floods). The AAL is then transformed to values between 0.0 and 1.0, where the maximum value corresponds to those AAL equal to or greater than 10‰[1] (or 1%). The normalization was made using the following functions per segment:

$$R_F = \begin{cases} 2\left(\dfrac{AAL}{AAL_{max}}\right)^2 & \text{for} \quad 0 \le AAL \le AAL_{max}/2 \\[2ex] 1-2\left(\dfrac{AAL}{AAL_{max}}\right)^2 & \text{for} \quad AAL_{max}/2 < AAL \le AAL_{max} \end{cases} \qquad (15.4)$$

where AAL_{max} is the AAL maximum value of normalization (10‰)

---

[1] 10‰ means a loss of USD 10 per thousand (USD 1.000) of the exposed value.
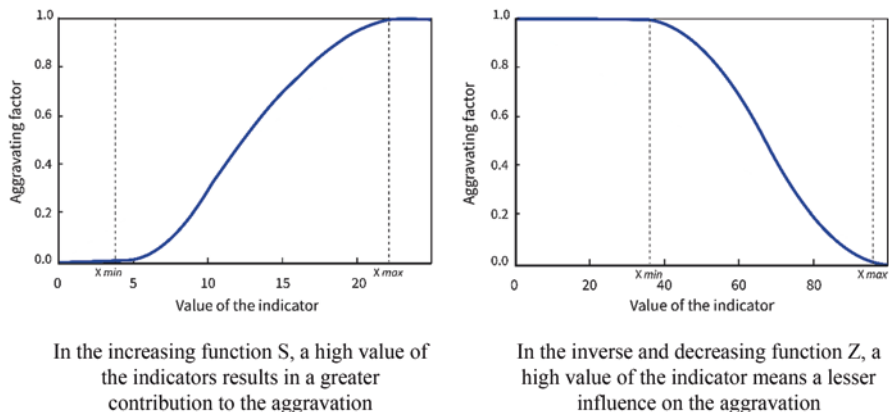
3.3 The Impact Aggravating Indicators

Underlying risk drivers that amplify physical risk are incorporated in an aggravating coefficient, F. This coefficient combines various aspects of society measured by indicators. These indicators are 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, and (iii) provide direct information about or are directly related to the contextual conditions within the two categories: social fragility F_{SF} and lack of resilience F_{FR}. The aggravating coefficient F is calculated as follows:

$$F = \sum_{i=1}^{m} F_{FSi} \cdot w_{FSi} + \sum_{j=1}^{n} F_{FRj} \cdot w_{FRj} \tag{15.5}$$

where F_{FSi} and F_{FRj} are the aggravating factors; w_{FSi} and w_{FRj} are the associated weights of each i and j factor; here, it is assumed that the weight of each factor is the same; m and n are the total number of factors for social fragility and lack of resilience, respectively. In this case, eight descriptors were used to capture the social fragility conditions and the other eight to capture the lack of resilience. As expected, these indicators are generated using various techniques, with different units of measurement. Likewise, each indicator has a greater or lesser degree of association with risk, as derived from the context, depending on the value it takes in each 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 quantitative risk scale. Therefore, a process of normalization and standardization is required to operate mathematically with the indicators and obtain consistent results. This process was made by using transformation functions.

The transformation functions can be understood as risk and aggravating probability distribution functions or as the membership functions of the linguistic benchmarking of high risk or high aggravation. The degree of association to the context-derived risk can be expressed in linguistic terms, as is it commonly done in expert-based assessment processes. In other words, an indicator of, for example, poverty has an increased association with the aggravation of physical risk (i.e., the higher the level of poverty, 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 in risk.

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

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

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

Fig. 15.4 Example of transformation functions S and Z

these types of functions, according to the range of values to be covered and the relevance of the indicator to reflect social fragility or lack of resilience, as appropriate. Figure 15.4 presents an example of 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), while 1.0 means full membership (or full contribution to the aggravating coefficient). $X_{\min}$ 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, 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. 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 w_{FSi} and w_{FRj} 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.

Finally, in this methodology it is assumed that the total risk, R_T, can have a maximum value of two times the physical risk. That is, according to a hypothetic case where contextual conditions are perfect and there is neither socio-economic fragility nor lack of resilience, the aggravating coefficient would be zero, and therefore the total risk may have the same value as the physical risk. On the other hand, if contextual conditions are as poor as to obtain the maximum value of the aggravating coefficient (1.0), R_T would reach twice the physical risk value. Although this assumption is arbitrary, if we consider F as the translation from the indicators to the

probability of a higher impact F, interpreted as a probability cannot be higher than 1.0. However, whether the influence of the socio-economic characteristics on the magnitude of a disaster is twice, three, four, or n times is not defined here, the objective in the context of the holistic evaluation is to make manifest the impact of these characteristics and show that they can influence the assessment of the most direct effects of a destructive event (physical damage). Risk, addressed from a physical point of view, is the starting point to analyze the subsequent impacts of a disaster. Disasters resulting from natural and anthropogenic events are the damages in the built environment or on the physical means affecting people and their activities in different ways.

4 Outcomes for the Disaster Risk Atlas

The holistic approach for risk assessment was carried out at a subnational level in Colombia for its 32 departments and 1123 municipalities, integrating physical risk resulting from a multi-hazard assessment and a set of socio-economic indicators. This section presents the results obtained using the methodology in terms of R_F, F, and R_T. Detailed information about the results and the Risk Atlas of Colombia can be found in UNGRD et al. (2018).

According to the results shown in Fig. 15.5, the highest R_F values are generally found in municipalities located in areas highly prone to floods where, in many cases, the area affected by an event represents virtually the whole municipal territory. In these cases, exposure plays an important role, given the intensity of the events and the small size of the territories that, in relative terms, result affected. Another reason for these high values of potential losses can be given by the disorganized growth and the lack of proper building and land-use codes. Usually, the larger the event and the smaller or the weaker the economy, the more significant is the impact.

Vulnerability, understood as a set of conditions that create risk through a process of social construction, is linked to the deficit in the coverage of basic needs, unbalanced economic development, weak governance, limited endogenous capacities, exclusion, and limited opportunities for access to credit, among other factors, often exacerbated by pressures that concentrate the populations in areas exposed to hazards. In the search for indicators, an effort was made to include relevant aspects that reflect social fragility and lack of resilience, in terms of conditions that represent comparatively unfavorable situations for expressing the degree to which different social groups face risk in a differentiated manner, making communities more vulnerable to hazards and consequently to the degradation of their environment. Differences in vulnerability within social and physical contexts determine the selective nature of the severity of the effects of natural and anthropogenic hazards. The variables or indicators seek to cover a wide spectrum of issues that underlie the notion of risk in terms of prevalent vulnerability conditions of physical susceptibility and beyond. Following these conditions, 16 variables were selected for this evaluation, covering the 1123 municipalities of the country.
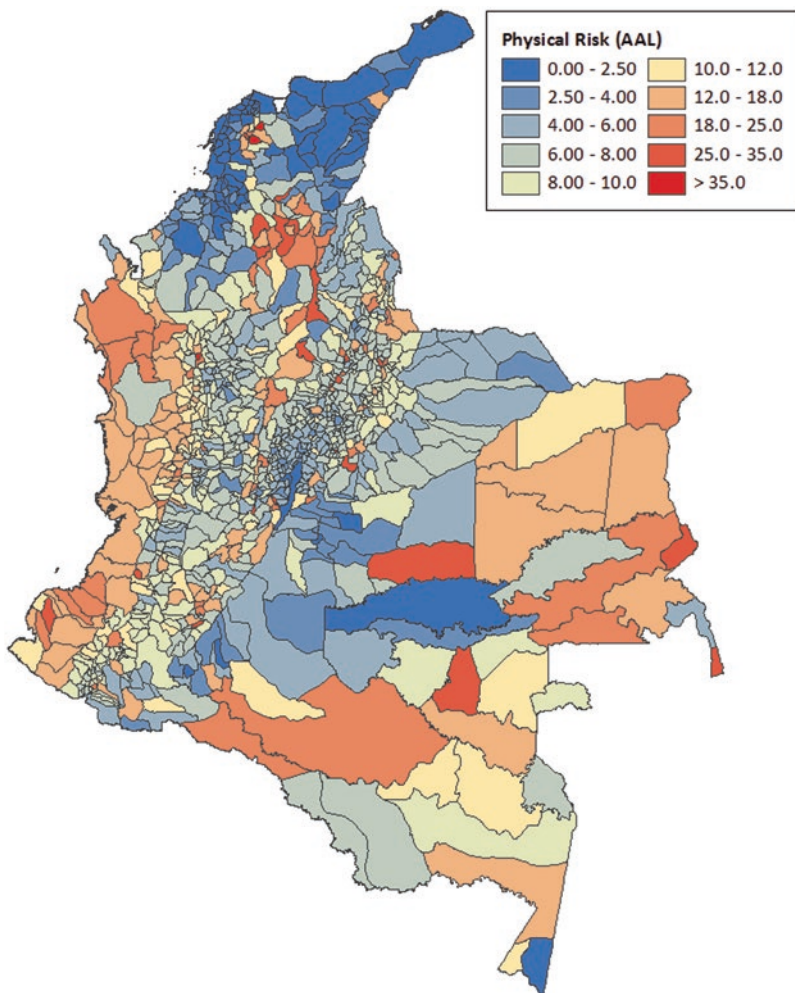
Fig. 15.5 Physical risk by municipality, AAL in relative values (‰)

Figure 15.6 shows a summary of the descriptors used in this analysis. Indicators denoted as F_{SFi} are related to social fragility, and the ones denoted as F_{LRi} are related to the lack of resilience.

These indicators seek to reflect, on the one hand, the predisposition to sustain damage due to social marginalization and segregation and to conditions of disadvantage and relative weaknesses related to socio-economic factors and on the other hand, the limitations to access and mobilize resources and the inability to face and recover from a negative impact. For example, indicators such as poverty and the unemployment rate reflect the (in)stability of the local economy, access to drinking water and other unsatisfied basic needs (UBN) reflect a situation of social marginalization, and the infant mortality rate reflects the state of health services and their

F_{SF1}	Population below the poverty line	Social fragility (SF)	Lack of resilience (LR)	Overall municipal performance index	F_{LR1}
F_{SF2}	UBN – Component housing			Municipal risk index	F_{LR2}
F_{SF3}	UBN – Crowded conditions			Tax revenues (per capita)	F_{LR3}
F_{SF4}	UBN – Drinking water and basic sanitation			Non-tax revenues (per capita)	F_{LR4}
F_{SF5}	UBN – Dependent population			Added value (per capita) – Econ. Importance	F_{LR5}
F_{SF6}	Infant mortality rate			Population living in the municipal center	F_{LR6}
F_{SF7}	Illiterate population			Business density	F_{LR7}
F_{SF8}	Unemployment			Health centers/ 10,000 inhabitants	F_{LR8}

Fig. 15.6 Indicators used for the calculation of the aggravating factor F

ability to respond to a negative impact. On the other hand, indicators such as the quality of institutions, connectivity, and tax revenues reflect the state of governance and institutional qualities, which by being stronger, will be better able to absorb the impact, respond, and recover from a disaster. Overall, the indicators selected reflect a notion of a community's susceptibility to being negatively impacted by potentially destructive events, whatever their nature or severity. From the socio-economic perspective, the highest values belong to weaker economies, where organizational, institutional, environmental, and social conditions are also weaker, and it is reflected in this evaluation by the high values of the aggravating factor, as is shown in Fig. 15.7. Roncancio et al. (2020) presented similar outcomes regarding social vulnerability.

Figure 15.8 shows the results of total risk R_T that illustrate the important influence that the aggravating factors have on physical risk. These results depict how most of the municipalities with the higher R_T values are in areas that face serious poverty problems, overwhelmed by ill-managed governance and are often neglected by the government, such as the case of many municipalities located on the Pacific coast and in the eastern region of the country. These results reflect susceptibility in terms of physical, organizational, and poor institutional conditions that may lead to the generation or increased vulnerability.

Figure 15.9 presents the total risk assessment at the departmental scale, also calculated for analysis and benchmarking purposes at the national level.
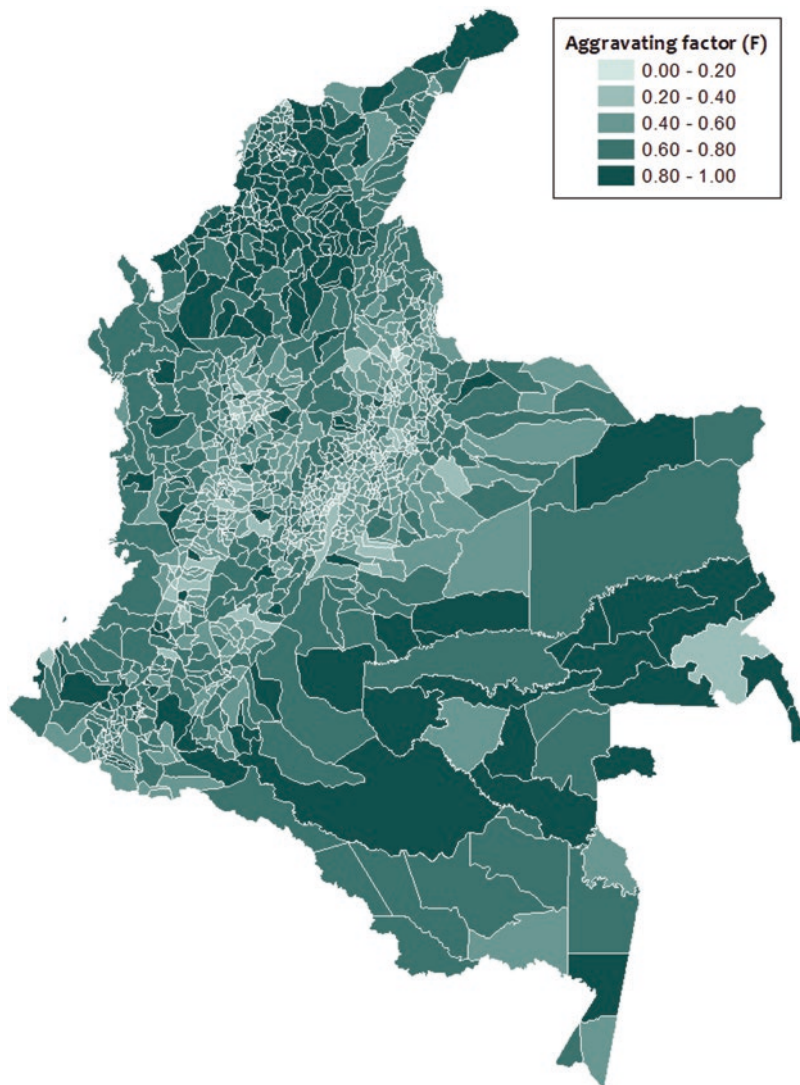
Fig. 15.7 Aggravating Factor by municipality, *F*

Table 15.1 presents the results of the holistic risk assessment by department. These results allow an overview for all of the country, useful for benchmarking purposes for national-level stakeholders.
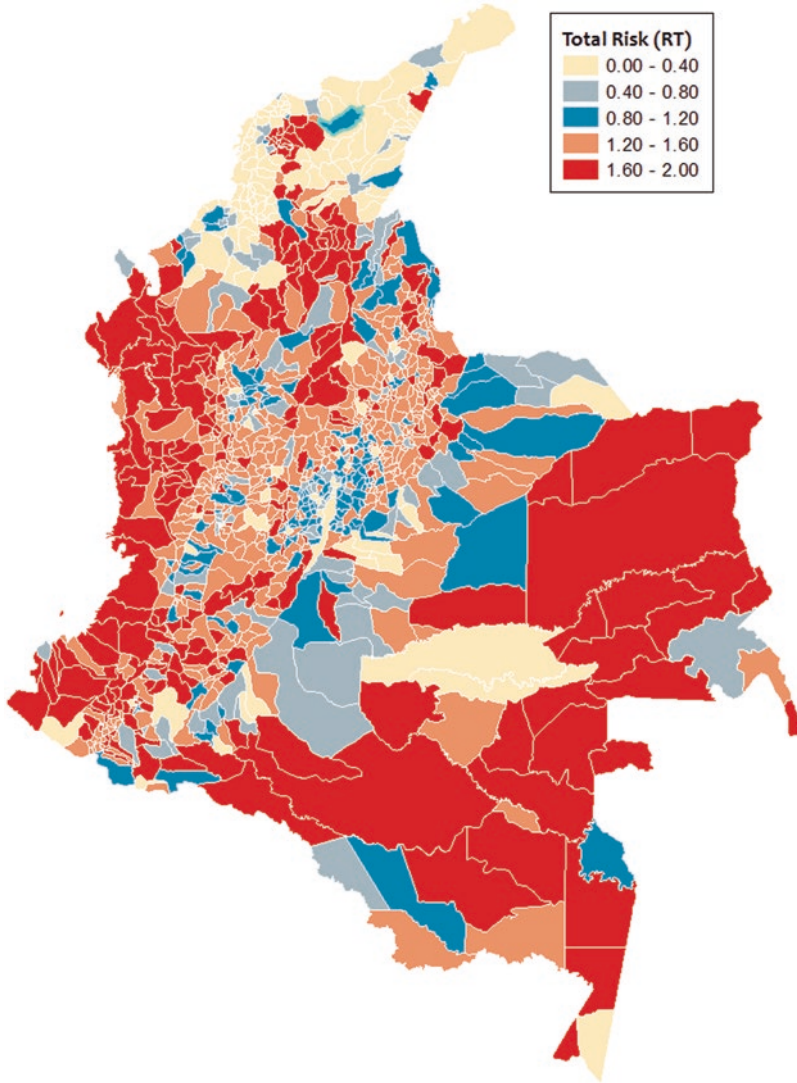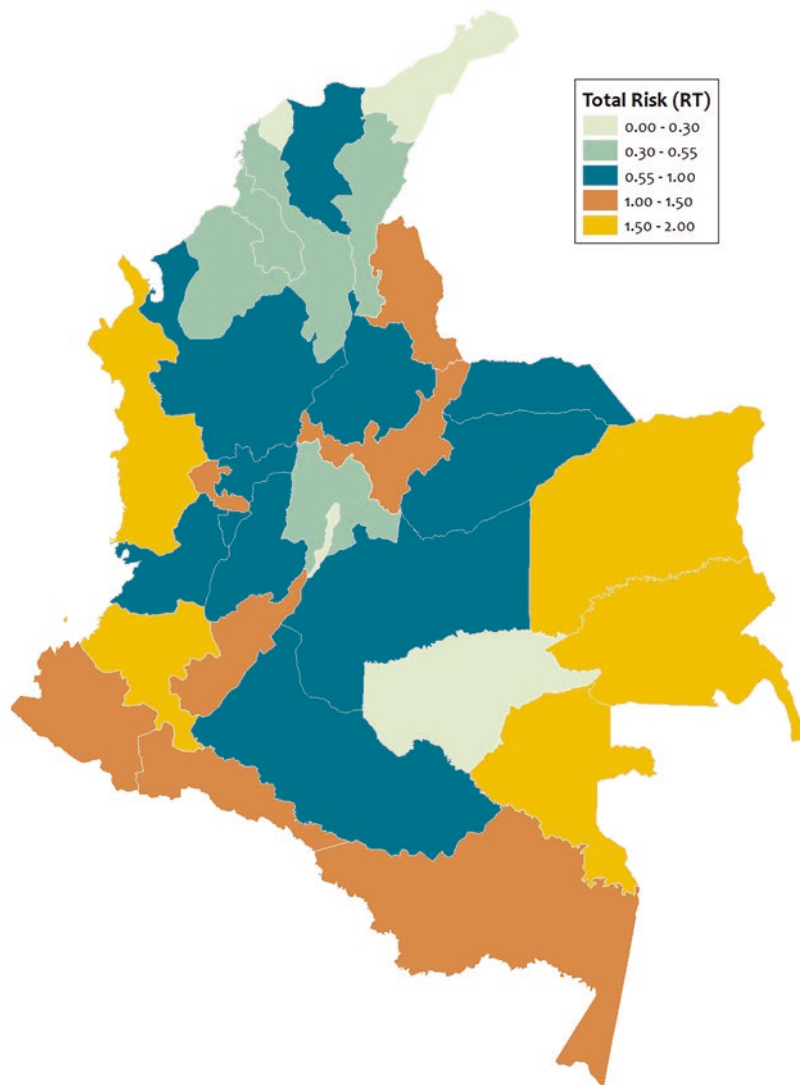
Fig. 15.8 Total risk by municipality R_T

Figure 15.10 presents the risk profile for the department of Cauca, generated under the framework of the Risk Atlas of Colombia.[2] The profile is a characterization depicting the results of a probabilistic risk assessment, including a map with the

---

[2]These profiles summarize the results obtained from a multi-hazard probabilistic risk assessment and a holistic risk assessment, aiming at facilitating the characterization of the departments, allowing a cross-departmental analysis for decision-making processes and the prioritization of actions for risk reduction. Department profiles can be found at UNGRD et al. (2018).

Fig. 15.9 Total risk by department, R_T

AAL relative values per municipality, graphics showing the loss exceedance probability for events of 100, 250, and 500 return periods, the contribution of each hazard to the AAL and the AAL ranking. For this department the hazard contributing the most to the AAL is earthquake, with 81.04%, followed by flood 18.19% and tsunami 0.77%. The profile also presents the PMLs (probable maximum loss) and the results of a holistic risk assessment at the departmental level, with the normalized values of the indicators used for its calculation. In Cauca, the aggravating coefficient is 0.66 that, together with its physical risk indicator value (0.96), make it one of the departments with the highest total risk level of Colombia.

Table 15.1 Results of risk assessment by department

Department	Exposed value [Col$ mill]	Multihazard AAL [Mill COP]	Multihazard AAL [‰]	Physical Risk RF	Aggravating factor F	Total Risk RT
Bogotá, D.C.	673,237,996	1,571,114	2.33	0.11	0.26	0.14
Antioquia	390,800,661	2,249,907	5.76	0.64	0.25	0.80
Valle del Cauca	206,158,652	1,245,904	6.04	0.69	0.26	0.86
Cundinamarca	142,770,958	598,105	4.19	0.35	0.23	0.43
Santander	117,600,856	655,420	5.57	0.61	0.26	0.77
Nariño	109,466,226	792,025	7.24	0.85	0.64	1.39
Cauca	80,980,218	697,753	8.62	0.96	0.66	1.59
Boyacá	65,354,569	492,024	7.53	0.88	0.36	1.19
Atlántico	94,915,760	134,340	1.42	0.04	0.38	0.06
Córdoba	89,499,737	276,138	3.09	0.19	0.62	0.31
Tolima	66,005,353	375,048	5.68	0.63	0.41	0.89
Caldas	60,518,762	392,269	6.48	0.75	0.32	0.99
Risaralda	46,033,970	294,574	6.40	0.74	0.38	1.02
Bolívar	86,893,370	280,886	3.23	0.21	0.63	0.34
Norte de Santander	44,181,140	293,876	6.65	0.78	0.49	1.16
Huila	47,239,842	362,534	7.67	0.89	0.48	1.32
Sucre	39,838,667	137,005	3.44	0.24	0.71	0.41
Chocó	29,644,140	322,495	10.88	1.00	0.70	1.70
Quindio	26,808,642	136,945	5.11	0.52	0.37	0.71
Magdalena	37,321,073	188,805	5.06	0.51	0.67	0.86
Cesar	33,650,937	110,053	3.27	0.21	0.61	0.34
La Guajira	27,460,452	61,480	2.24	0.10	0.73	0.17
Meta	20,857,744	94,596	4.54	0.41	0.34	0.55
Caquetá	28,047,658	142,341	5.07	0.51	0.68	0.86
Casanare	12,557,006	74,102	5.90	0.66	0.50	1.00
Arauca	7,749,719	36,712	4.74	0.45	0.61	0.72
Putumayo	10,110,582	74,160	7.33	0.86	0.60	1.37
Guaviare	6,271,236	15,043	2.40	0.12	0.72	0.20
Archip. San Andrés	2,497,720	9,643	3.86	0.49	0.49	0.44
Vichada	2,012,009	32,388	16.10	1.00	0.80	1.80
Vaupés	1,510,898	18,321	12.13	1.00	0.76	1.76
Guainia	664,937	13,187	19.83	1.00	0.90	1.90
Amazonas	2,055,236	12,476	6.07	0.69	0.74	1.20

As it can be seen, the evaluation performed in Colombia covered different levels of data, information, and analysis, seeking to best communicate risk to the different stakeholders involved in disaster risk management. Table 15.2 presents the results of a risk assessment at the municipal level for the 42 municipalities in the department of Cauca, which includes the multi-hazard AAL (in millions of Colombian Pesos, COP, and their relative values in ‰), physical risk, aggravating factors, and total risk. In Cauca, almost all municipalities (34) reached the R_T values higher than 1.5 and also the F values higher than 0.5, which reflects poor overall socio-economic conditions. Likewise, most municipalities obtained the maximum R_F value, indicating a high susceptibility of the built environment, resulting from poor planning, institutional weaknesses, and probable conditions social and economic disadvantage forcing populations to settle in areas expose to hazards. The results, disaggregated at the municipal level, allow drawing attention to those unfavorable situations, in turn, disaggregated in indicators, and depict the more urgent areas for intervention.
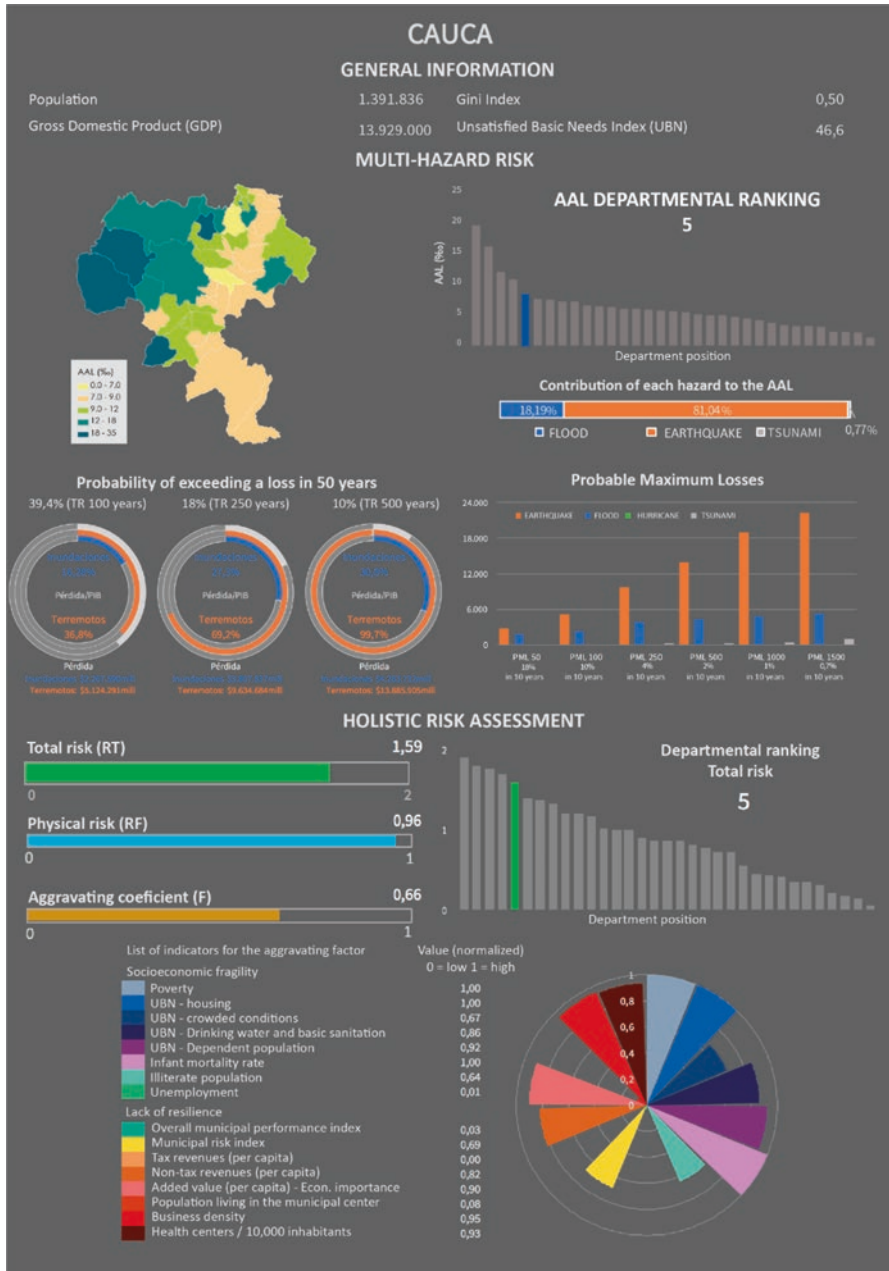
Fig. 15.10 Department risk profile depicting a holistic risk assessment, Cauca, Colombia

Table 15.2 Results of risk assessment for the municipalities of the department of Cauca, Colombia

Municipality	Multi-hazard AAL [Million COP]	Multi-hazard AAL [‰]	RF	F	RT
Argelia	$ 15,151	16.16	1.00	0.85	1.85
Sucre	$ 2,535	9.15	0.99	0.81	1.78
Suárez	$ 31,812	34.34	1.00	0.75	1.75
Mercaderes	$ 35,833	21.86	1.00	0.73	1.73
El Tambo	$ 23,749	15.88	1.00	0.73	1.73
Timbiquí	$ 15,232	18.43	1.00	0.72	1.72
López	$ 11,139	16.01	1.00	0.71	1.71
Guapi	$ 22,825	18.82	1.00	0.71	1.71
Balboa	$ 6,064	8.96	0.98	0.74	1.71
Almaguer	$ 7,904	8.62	0.96	0.77	1.70
Sotara	$ 6,148	8.99	0.98	0.72	1.68
Toribío	$ 7,128	8.65	0.96	0.73	1.67
La Sierra	$ 3,469	9.15	0.99	0.69	1.67
Paez	$ 12,305	10.26	1.00	0.66	1.66
Santa Rosa	$ 10,613	8.61	0.96	0.72	1.65
La Vega	$ 11,677	9.03	0.98	0.68	1.65
Caldono	$ 9,950	9.61	1.00	0.65	1.64
Bolívar	$ 19,258	10.60	1.00	0.64	1.64
Morales	$ 9,252	10.09	1.00	0.62	1.62
Jambaló	$ 5,294	8.80	0.97	0.66	1.61
Inzá	$ 14,227	12.18	1.00	0.61	1.61
Puracé	$ 6,519	8.35	0.95	0.70	1.61
Patía	$ 18,862	10.10	1.00	0.61	1.61
San Sebastián	$ 3,972	8.99	0.98	0.64	1.61
Miranda	$ 14,511	8.72	0.97	0.66	1.60
Totoró	$ 6,445	8.61	0.96	0.66	1.60
Buenos Aires	$ 14,436	16.59	1.00	0.59	1.59
Guachené	$ 4,251	10.23	1.00	0.59	1.59
Florencia	$ 1,805	9.24	0.99	0.60	1.59
Cajibío	$ 15,911	11.05	1.00	0.59	1.59
Rosas	$ 4,743	8.21	0.94	0.64	1.54
Piendamó	$ 12,193	8.70	0.97	0.57	1.52
Corinto	$ 8,130	8.66	0.96	0.56	1.50
Piamonte	$ 1,677	7.22	0.85	0.77	1.50
Villa Rica	$ 29,230	9.63	1.00	0.50	1.49
Padilla	$ 4,829	10.11	1.00	0.47	1.47
Puerto Tejada	$ 13,895	9.48	0.99	0.48	1.47
Caloto	$ 14,711	12.03	1.00	0.43	1.43
Timbío	$ 13,242	7.77	0.90	0.57	1.42
Silvia	$ 11,684	7.98	0.92	0.54	1.41
Santander de Quilichao	$ 40,030	6.91	0.81	0.43	1.16
Popayán	$ 175,109	5.23	0.54	0.33	0.73

5 Conclusions

This is the first time that a comprehensive holistic and total risk assessment methodology is conducted at the subnational level for a whole country. The holistic approach summarizes, in a single number R_T, the occurrence of hazard events, exposure and vulnerability, physical risk (calculated using probabilistic models that incorporate the uncertainty associated with the loss occurrence process), and the contextual conditions in which disasters might occur, as determined by aggravation coefficient F. These characteristics make R_T a unique useful index providing highly relevant information for risk management and decision-making processes. Total risk is a comparative index allowing the identification of the territorial units with the highest levels of risk, allowing identifying and prioritizing the performance of more detailed risk assessments, as well as actions and policies for effective risk management and sustainable development.

From the context-derived risk 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 strategies. The analysis of these indicators and the aspects they reflect make it possible to focus efforts on nonphysical aspects of risk management. In the case of Cauca department, for instance, some of the indicators with the largest contribution to the aggravating coefficients are poverty, unsatisfied basic needs, infant mortality rate, and the lower added value per capita (economic importance).[3] This indicates, in general terms, that the economic situation of the department is unfavorable, a reality that coupled with weak institutions, condition a propensity to risk and the creation of new risk. While attacking economic inequalities is neither simple nor swift, it is possible, for example, to justify a housing improvement program, which directly faces the cause reflected in indicator F_{FS2} and indirectly F_{FS3} and F_{FS4}. Note that although it might seem obvious that housing improvement is required in many municipalities, it was not obvious that risk was exacerbated by the same aspects. Furthermore, indicators also allow for a comparison between different periods, which makes the holistic approach a useful tool for the evaluation and monitoring of risk management strategies and policies.

Although uncertainties related to physical risk assessment have been accounted for, further research is needed to incorporate the ones existing in the considered socio-economic characteristics (Burton & Silva, 2014). Those cannot be handled utilizing probability distributions. Nevertheless, it is important to highlight that sensitivity tests have been made to demonstrate the robustness of risk rankings and risk level ranges derived from the risk composite indicator Marulanda et al. (2009).

This kind of evaluation must be periodically updated to evaluate the changes in physical risk and development through time. The results obtained also allow measuring the progress toward 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).

Finally, the development of Atlas of multi-hazard risk using a holistic, multisectoral, and interdisciplinary approach is a task to achieve in each country. This effort of risk science is a key step to provide the risk landscape that is emerging at different scales and sectors. Risk is really complex, systemic, and cascading, and it is necessary to take into account its distinct dimensions and interdependencies. This comprehensive perspective of risk 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, and addressing the factors exacerbating disaster risk, with prominence given to the issues of justice and equity.

---

[3] Economic importance means the relative weight represented by the Gross Domestic Product of each of the departments within the country.

References

Ambraseys, N. (2010). A note on transparency and loss of life arising from earthquakes. *Journal of Seismology and Earthquake Engineering, 12*(3), 83–88. https://www.sid.ir/en/journal/ViewPaper.aspx?id=213107

Apostolakis, G. (1990). The concept of probability in safety assessments of technological systems. *Science, 250*(4986), 1359–1364. https://doi.org/10.1126/science.2255906

Bankoff, G., Frerks, G., & Hilhorst, D. J. M. (2004). *Mapping vulnerability: Disasters, development and people*. London, UK.

Barbat, A., Carreño, M. L., Cardona, O. D., & Marulanda, M. (2011). Evaluación holística del riesgo sísmico en zonas urbanas. *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería, 27*(1), 2–27. https://upcommons.upc.edu/handle/2117/77680

Bernal, G., Cardona, O. D., Marulanda, M. C., & Carreño, M. L. (2019). *On the calculation of the loss exceedance curve and related risk metrics*. Technical Note. INGENIAR.

Bernal, G., Salgado-Gálvez, M., Zuloaga, D., Tristanchi, J., González, D., & Cardona, O. D. (2017). Integration of probabilistic and multi-hazard risk assessment within urban development planning and emergency preparedness and response: Application to Manizales, Colombia. *International Journal of Disaster Risk Science*. https://doi.org/10.1007/s13753-017-0135-8

Birkmann, J., Cardona, O. D., Carreño, M. L., Barbat, A. H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P., & Welle, T. (2013). Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards, 67*(2), 193–211. https://doi.org/10.1007/s11069-013-0558-5

Burton, C., Khazai, B., & Silva, V. (2014). *Social vulnerability and integrated risk assessment within the global earthquake model*. 10th US National Conference on Earthquake Engineering, USA.

Burton, C., & Silva, V. (2014). *Integrated risk modeling within the global earthquake model (Gem): Test case application for Portugal*. 2nd European Conference on Earthquake Engineering and Seismology. https://www.researchgate.net/publication/265915488_Integrated_Risk_Modeling_Within_The_Global_Earthquake_Model_Gem_Test_Case_Application_For_Portugal

Cardona, O. D. (1986). Estudios de vulnerabilidad y evaluación del riesgo sísmico: Planificación física y urbana en áreas propensas. Asociación Colombiana de Ingeniería Sísmica. Reporte AIS-33. Diciembre 1986. Bogotá. Colombia.

Cardona, O. D. (2001). *Estimación holística del riesgo sísmico utilizando sistemas dinámicos complejos*. Universidad Politécnica de Cataluña.

Cardona, O. D. (2004). The need for rethinking the concepts of vulnerability and risk from a holistic perspective: A necessary review and criticism for effective risk management. In *Mapping vulnerability: Disasters, development and people* (pp. 38–51). Earthscan Publishers.

Cardona, O. D., Ordaz, M. G., Mora, M., Salgado-Gálvez, M. A., Bernal, G. A., Zuloaga-Romero, D., Marulanda, M. C., Yamín, L., & González, D. (2014). Global risk assessment: A fully probabilistic seismic and tropical cyclone wind risk assessment. *International Journal of Disaster Risk Reduction., 10*, 461–476.

Carreño, M. L. (2006). Técnicas innovadoras para la evaluación del riesgo sísmico y su gestión en centros urbanos Acciones ex ante y ex post. In *TDX (Tesis Doctorals en Xarxa)*. Universitat Politècnica de Catalunya. http://www.tdx.cat/handle/10803/6241

Carreño, M. L., Cardona, O. D., & Barbat, A. H. (2007). Urban seismic risk evaluation: A holistic approach. *Natural Hazards, 40*(1), 137–172. https://doi.org/10.1007/s11069-006-0008-8

Cornell, C. A. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America, 58*(5), 1583–1606.

Daniell, J., Daniell, K., Daniell, T., & Khazai, B. (2010). *A country level physical and community risk index in the Asia-Pacific region for earthquakes and floods*. Paper No. 0392. 5th International Civil Engineering Conference in the Asian Region (CECAR).

Esteva, L. (1967). Criterios para la construcción de espectros para diseño sísmico. *Tercer Simposio Panamericano de Estructuras*. Caracas, Universidad Central de Venezuela.

FEMA. (2020). *The National Risk Index*. Available at: https://hazards.geoplatform.gov/portal/apps/MapSeries/index.html?appid=ddf915a24fb24dc8863eed96bc3345f8

Grossi, P., & Kunreuther, H. (2005). *Catastrophe modeling: A new approach to managing risk* (p. 252). Springer Science and Business Media. ISBN: 0387231293, 9780387231297.

Jaimes, M., Reinoso, E., & Esteva, L. (2015). Risk analysis for structures exposed to several multi-hazard sources. *Journal of Earthquake Engineering, 19*(2), 297–312. https://doi.org/10.1080/13632469.2014.962673

Jamali, A. A., Arianpour, M., Piraseh, S., & Eslamian, S. (2022). Geospatial techniques flood hazard, vulnerability and risk mapping in GIS geodata analytical process in Boolean, AHP, and Fuzzy Models, Ch. 20. In S. Eslamian & F. Eslamian (Eds.), *Flood handbook, Vol. 2: Flood analysis and modeling*. Taylor and Francis, CRC Group.

Jaramillo, N. (2014). *Evaluación holística del riesgo sísmico en zonas urbanas y estrategias para su mitigación : aplicación a la ciudad de Mérida-Venezuela*. Universidad Politécnica de Cataluña.

Jenkins, S. F., Magill, C. R., McAneney, J., & James, B. R. (2012). Regional ash fall hazard I: A probabilistic assessment methodology. *Bulletin of Volcanology, 74*(7), 1699–1712.

Khazai, B., Khazai, B., Bendimerad, F., & Cardona, O. D. (2015). *A guide to measuring urban risk resilience*. Earthquakes and Megacities Initiative. http://emi-megacities.org/wp-content/uploads/2015/03/ResilienceIndicators_Pre-release_March20151.pdf

Marulanda, M. C., Cardona, O. D., & Barbat, A. H. (2009). Robustness of the holistic seismic risk evaluation in urban centers using the USRi. *Natural Hazards, 49*(3), 501–516. https://doi.org/10.1007/s11069-008-9301-z

Marulanda, M. C., Cardona, O. D., Marulanda, P., Carreño, M. L., & Barbat, A. H. (2020). Evaluating risk from a holistic perspective to improve resilience: The United Nations evaluation at global level. *Safety Science, 127*. https://doi.org/10.1016/j.ssci.2020.104739

Marulanda, M. C., Carreño, M. L., Cardona, O. D., Ordaz, M. G., & Barbat, A. H. (2013). Probabilistic earthquake risk assessment using CAPRA: Application to the city of Barcelona, Spain. *Natural Hazards, 69*(1), 59–84. https://doi.org/10.1007/s11069-013-0685-z

Muir-Wood, R. (2016). *The cure for catastrophe: How we can stop manufacturing natural disasters*. Basic Books.

Niño, M., Jaimes, M., & Reinoso, E. (2015). Seismic-event-based methodology to obtain earthquake induced translational landslide regional hazard maps. In *Natural Hazards*. Springer Ed. https://doi.org/10.1007/s11069-014-1163-y

Oliver-Smith, A. (2004). Theorizing vulnerability in a globalized world: A political ecological perspective. In G. Bankoff, G. Frerks, & D. Hilhorst (Eds.), *Mapping vulnerability: Disasters, development and peoplem* (pp. 10–24).

Ordaz, M. (2000). *Metodología para la evaluación del riesgo sísmico enfocada a la gerencia de seguros por terremoto*. Universidad Nacional Autónoma de México.

Quijano, J. A., Jaimes, M. A., Torres, M. A., Reinoso, E., Castellanos, L., Escamilla, J., & Ordaz, M. (2014). Event-based approach for probabilistic agricultural drought risk assessment under rainfed conditions. *Journal of the International Society for the Prevention and Mitigation of Natural Hazards, 76*, 1297–1318. https://doi.org/10.1007/s11069-014-1550-4

Roncancio, D. J., Cutter, S. L., & Nardocci, A. C. (2020). Social vulnerability in Colombia. *International Journal of Disaster Risk Reduction, 50*, 101872. https://doi.org/10.1016/j.ijdrr.2020.101872

Salgado-Gálvez, M., Bernal, G., Zuloaga, D., Marulanda, M., Cardona, O. D., & Henao, S. (2017). Probabilistic seismic risk assessment in Manizales, Colombia: Quantifying losses for insurance purposes. *International Journal of Disaster Risk Science*. https://doi.org/10.1007/s13753-017-0137-6

Salgado-Gálvez, M. A., Cardona, O. D., Carreño, M. L., & Barbat, A. H. (2015). *Probabilistic seismic hazard and risk assessment in Spain*. Monographs on earthquake engineering. International Center for Numerical Methods in Engineering – CIMNE. ISBN: 978-84-993307-7-3.

Salgado-Gálvez, M. A., Zuloaga, D., Bernal, G., Mora, M. G., & Cardona, O. D. (2014). Fully probabilistic seismic risk assessment considering local site effects for the portfolio of buildings in Medellín, Colombia. *Bulletin of Earthquake Engineering, 12*, 671–695.

Salgado-Gálvez, M. A., Zuloaga, D., Velásquez, C. A., Carreño, M. L., Cardona, O. D., & Barbat, A. H. (2016). Urban seismic risk index for Medellín, Colombia, based on probabilistic loss and casualties estimations. *Natural Hazards, 80*(3), 1995–2021. https://doi.org/10.1007/s11069-015-2056-4

UNDP. (2004). *A global report: Reducing disaster risk a challenge for development.* Available at: https://www.undp.org/content/undp/en/home/librarypage/crisis-prevention-and-recovery/reducing-disaster-risk%2D%2Da-challenge-for-development.html

UNDRR. (2017). *The GAR Atlas: Unveiling global disaster risk.* Available at: https://www.preventionweb.net/english/hyogo/gar/atlas/

UNGRD, Cardona, O.D., Bernal G., Marulanda, P., Villegas, C., González, D., Escovar, M.A., Carreño, M.L., & Marulanda, M.C. (2018). *Atlas de riesgo de Colombia: Revelando los desastres latentes.* Available at: https://repositorio.gestiondelriesgo.gov.co/handle/20.500.11762/27179

Wong, I. G. (2014). How big, how bad, how often: Are extreme events accounted for in modern seismic hazard analysis? *Natural Hazards, 72*(3), 1299–1309. https://doi.org/10.1007/s11069-013-0598-x