Chapter

Toward a New Conceptual and Methodological Approach for the Integral Evaluation of Volcanic Risk

Leonel Vega

Abstract

In the world, there are very few experiences of studies oriented to the integral evaluation of risks due to natural hazards. In the case of volcanic risk, most of the scientific-technical and economic efforts have been oriented mainly toward the evaluation of threats, with few methodological considerations to assess vulnerability and much less risk. In other cases, the threat and vulnerability are evaluated independently, with many difficulties for the comprehensive risk assessment. Many of the studies called "vulnerability assessments" are only physical and functional characterizations and diagnoses of vital infrastructure and population. These characterizations can hardly be interpreted in terms of georeferenced indices and/or vulnerability maps that represent the spatial and temporal exposure of the elements exposed to each threat and, even less, that represent the intrinsic and extrinsic response capacities of these elements in comparison with the threats. In this chapter, a new conceptual and methodological approach is proposed for the integral evaluation of volcanic risk, which includes the generation and adjustment of a new equation for the determination of volcanic risk, based on the integral assessment of threats and vulnerabilities.

Keywords: volcanic threat, vulnerability, volcanic risk index, intrinsic and extrinsic response capabilities, maps of risk

1. Introduction

So far, there is no technique to accurately predict the occurrence of a volcanic eruption. Some of the phenomena presented by volcanoes such as seismic activity (tremors, etc.), soil deformation, gas emissions, or fumarolic activity and the chemical composition of water and its vapors help scientists to know when a volcano begins to activate. If changes in these phenomena can be detected, it is possible to establish some degree of probability of a volcanic eruption, although it is impossible to predict the day, time, and size of an eruption [1].

To detect these changes, volcanic observatories have been installed in various volcanoes around the world for several years, equipped with a series of equipment that has been collecting valuable information, allowing in some cases to predict at least the time when the activity would begin in the surface and the place where the materials would be emitted [2–4]. Anyway, volcanoes have individual behaviors, so it is necessary to make a permanent and specific follow-up to each one, because although it is true there are some features common to all, there are others that individualize them [5–7].

It is also important to investigate the history of each volcano through the identification, petrographic analysis, and dating of its multiple pyroclastic deposits, to determine the characteristics that typify them [8, 9]. With this information and other knowledge, it is possible to elaborate, for example, maps of volcanic threats, which although they do not allow to determine when the next eruption will be, if they allow to determine an approximate order of the magnitude of the event and of the areas of affectation [10].

In fact, in the world, there are very few experiences of studies oriented to the integral evaluation of risk in the face of natural hazards. So much so that in the case of volcanic risk, most of the scientific-technical and economic efforts have been oriented mainly toward the evaluation of threats, with few methodological considerations for the evaluation of vulnerability and much less of the risk [11]. In other cases, the threat and vulnerability are evaluated independently, which logically presents many difficulties for the integral risk assessment. It is also easy to verify that many of the studies called "vulnerability assessments" are only physical and functional characterizations and diagnoses of vital infrastructure and population [12–14]. These characterizations can hardly be interpreted in terms of georeferenced indexes and/or maps of vulnerability that represent the spatial and temporal exposure of the elements exposed to each threat, much less that they represent the intrinsic and extrinsic response capacities of these elements compared to the threats.

What is required, then, is to define to whom and to what this event could affect, its degree of vulnerability to the threat, and the level of risk to which it is subjected, as basic inputs for decision-making and comprehensive risk management.

In this chapter of book, in light of the process of "Systemic Parametrization of the Environmental Dimension" [15], a summary of the conceptual and methodological approach developed by the undersigned is presented through the PIGA Group for Research in Politics, Information, and Management Environmental of the Universidad Nacional de Colombia, to carry out the studies and analysis of vulnerability and risk in a sector of the area of influence of the Cerro Machín volcano [16], taking as a starting point the study of the volcanic threat previously advanced by the former Colombian Institute of Geology and Mining [17].

Finally, some general conclusions and recommendations are presented with the hope that this new approach constitutes another grain of sand in the difficult task of protecting human beings and their environment from natural threats, particularly from volcanic threats, all through of an integral management of the risk that evaluates and anticipates the threats in a timely manner, that adequately plans and budgets the policies, strategies, instruments, and protocols to be followed in front of them, and that responds with effectiveness against the handling of emergencies and contingencies. In any case, it is expected to understand that "there are no natural disasters but political and management disasters."

2. New conceptual approach

Traditionally, the definition of risk (R) refers to the probability that something harmful will happen on a given element [18]. The simplest conceptual expression to express the risk has been $R = A. V$, where A is the threat, understood as a latent condition derived from the probability of occurrence of a physical phenomenon of natural, socio-natural, or anthropic unintentional origin that it can cause damage to the element or group of exposed elements, and V is the vulnerability, understood as the susceptibility or characteristic of the element or group of elements to be totally or partially damaged by the impact of the threat [19].

In the development of this chapter of book, a new conceptual and methodological approach is proposed for the integral evaluation of volcanic risk, which includes the generation and adjustment of a new equation for the determination of volcanic risk, based on the integral assessment of threats and vulnerabilities.

2.1 Threat analysis

Consistent with [18, 19], the threat represents the potential for damage of a natural phenomenon and is calculated by quantifying the energy that is applied to a particular site of interest or unit of analysis.

For the purposes of this study, it is assumed that the energy of a threat (as well as that of an environmental impact) can be represented qualitatively according to its intrinsic characteristics of probability of occurrence, intensity, duration, extension, accumulation, synergy, etc. [20], and, therefore, the quantification of this energy is done by means of an index that represents dimensionally and under the same scale the intrinsic characteristics of the different volcanic threats considered.

Consequently, taking as reference, the equation model that calculates the intrinsic importance in environmental impacts [20], the intrinsic threat index (Å) is calculated for each threat j of each analysis scenario based on its main intrinsic characteristics as shows in Eq. (1):

$$\text{Å}_j = \mathrm{P}\left(0{,}6.I_j + 0{,}2.D_j + 0{,}1.E_j + 0{,}1.A_j\right) \tag{1}$$

where Å is the intrinsic threat index, P is the probability of occurrence, I is the intensity of the threat, D is the duration of the threat, E is the extension of the threat, and A is the accumulation of the threat.

For the qualitative assessment of each of the characteristics that determine the intrinsic threat index, the environmental impact assessment model is taken as a reference [20], and **Table 1** is generated where the different assessment categories are proposed.

INTRINSIC THREAT	Threat index calculated for each threat j in the units of analysis. It depends on its probability of occurrence and its intrinsic characteristics of intensity, duration, extension and accumulation.	Irrelevant	0 - 0.24
		Moderate	0.25 - 0.49
		Severe	0.50 - 0.74
		Critical	0.75 - 1.00
PROBABILITY OF OCCURRENCE	Probability of occurrence of the threat	Nula	0
		Total	1
INTENSITY	The amount of energy that manifests itself, in the unit of analysis, is related to the destructive potential of the threat	Low	0,001
		Media	0,01
		High	0,1
		Very High	1
DURATION	Duration of the threat occurring, in the unit of analysis. Immediate (less than hours), medium term (hours to days), long term (days to weeks)	Righ now	0,01
		Medium term	0,1
		Long term	1
EXTENSION	Coverage that has the threat in the unit of analysis	Nula	0
		Partial	0.1-0.9
		Total	1
ACCUMULATION	A threat is cumulative if it manifests itself in the unit of analysis several times and this increases its potential for damage.	Simple	0,1
		Cumulative	1

Table 1.
Valuation of the intrinsic threat index.

2.2 Vulnerability analysis

For the purposes of this study, vulnerability will be associated with the ability of an element or group of elements not to be totally or partially damaged by the impact of a threat [21]. Conceptually, it will be a function of the degree of spatial and temporal exposure, and of the intrinsic and extrinsic response capacity of the exposed elements.

In order to be able to mathematically integrate the intrinsic threat index (Å) with the vulnerability values, with the help of the Excel tool and after successive tests with field information, Eq. (2) is generated and adjusted for the vulnerability index (V), which is calculated for each exposed element i against each threat j, as described below:

$$V = SE.TE.(1 - IRC)^{1+\propto.ERC} \tag{2}$$

where V is the vulnerability index, SE is the space exhibition, TE is the temporary exhibition, IRC is the intrinsic response capacity, ERC is the extrinsic response capacity, and α is the form coefficient used in the adjustment of the family of curves corresponding to the vulnerability Eq. (2) (see **Figure 1**).

For the qualitative assessment of each of the characteristics that determine the vulnerability index, **Table 2** is generated, where the different assessment categories are proposed.

2.2.1 The intrinsic response capacity (IRC)

For the purposes of this study, the intrinsic response capacity (IRC) will be understood as an index that represents dimensionally the capacity of each exposed element (ecosystem, constructed, population) to react and/or physically resist the impact of a threat and/or recover later by itself from the affectation caused.

The IRC is based on the concept of resilience, whose definition of the term comes from the field of physics, referring to "the ability of a material to recover its original form after having been subjected to high pressures," and that in its broadest sense, it is described as "elasticity" [11]. Later, due to multiple similarities and analogies, the concept of resilience extended to the field of natural and social systems but, in any case, always denoting "the degree to which a system recovers or returns to its previous state before the action of an external stimulus" [12].

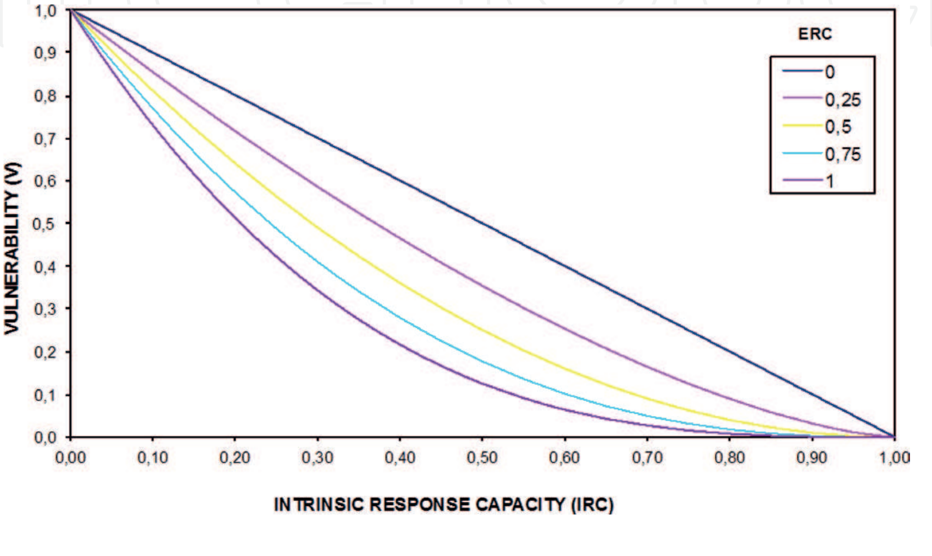

Figure 1.
Family of curves in the vulnerability equation (V).

V	VULNERABILITY	Vulnerability Index, calculated for each exposed element i of the environment against each threat j. It is a function of the degree of spatial and temporal exposure and the intrinsic and extrinsic response capacity of the exposed elements.	Irrelevant	0 - 0.24
			Moderate	0.25 - 0.49
			Severe	0.50 - 0.74
			Critical	0.75 - 1.00
SE	SPACE EXPOSURE	Degree of spatial exposure of the element to the threat. It is classified according to the space or area exposed to the threat classified as a percentage, for which the GIS is used.	No one	0,00
			Low	0,25
			Media	0,50
			High	0,75
			Very high	1,00
TE	TEMPORAL EXPOSITION	Generally the temporary exposure corresponds to the useful life of the element. For deterministic scenarios, it corresponds with the time the exposed element lasts when the threat occurs.	No one	0,00
			Hours to days	0,25
			Days to weeks	0,50
			Weeks to months	0,75
			Permanent	1,00
IRC	INTRINSIC RESPONSE CAPACITY	The capacity of the exposed element (ecosystem, built, population) to react and physically resist the impact of a threat and to subsequently recover by itself from the affectation caused.	No one	0,00
			Low	0,25
			Media	0,50
			High	0,75
			Very high	1,00
ERC	EXTRINSIC RESPONSE CAPACITY	Institutional capacity to comprehensively manage risk in compliance with the basic systemic functions of planning, management and evaluation.	No one	0,00
			Low	0,25
			Media	0,50
			High	0,75
			Very high	1,00

Table 2.
Assessment of the vulnerability index.

Consequently, the IRC will depend on each type of threat in particular and will be calculated independently for each element exposed based on a weighted assessment of attributes, according to the generic Eq. (3):

$$IRC = \frac{\sum Pn.Wn}{Pn_{máx}} \tag{3}$$

where IRC is the intrinsic response capacity, Pn is the evaluation of attributes according to characteristics of each exposed element, and Wn is the weighting factor.

The intrinsic ecosystem response capacity (ICRe) is defined as the capacity of an ecosystem to react and physically resist the impact of a threat and subsequently recover by itself from the damage caused. It depends on each type of threat in particular and can be calculated independently for each exposed element of the ecosystem (rivers, páramos, forests and stubble, pastures, and crops) based on a weighted assessment of descriptors and attributes related to the environmental state of the ecosystems, in terms of quantity, quality, and ecological availability of environmental goods and services, and the degree of intervention or anthropic pressure, in terms of the use and deterioration caused on said environmental goods and services [16, 20].

The intrinsic response capacity of constructed elements (IRCc) is defined as the capacity of a constructed element to physically resist the impact of a threat and to maintain its functionality after the affectation received. It depends on each type of threat in particular and can be calculated for each exposed constructed element (buildings, roads, infrastructures) based on the weighted assessment of descriptors and attributes related to their physicochemical characteristics such as construction material (from the structure, elements, base, subbase), the structure (type, mezzanines, anchors), the roof (type of roof), the covering (type of covering), the rolling (rolling layer), the terrain (ground, slope), drains (quantity and condition of drainage works), and general condition (age, conservation, damage) [5, 14, 16].

The intrinsic response capacity of the population (IRCp) is defined as the capacity of a given population to react and physically resist the impact of a threat and subsequently recover by itself from the affectation caused. It can be calculated for an exposed population group based on a weighted assessment of descriptors and attributes related to planning (perception of risk, level of education, unsatisfied basic needs, participation in drills, participation in emergency committees, knowledge of evacuation routes and shelters), the operation (optimal evacuation distance, type and quality of route, population to be mobilized, active and passive human resources, physical and/or psychological limitations), and logistics (means of transport and communication equipment) [11, 12, 16].

2.2.2 The extrinsic response capacity (ERC)

For the purposes of this study, the extrinsic response capacity (ERC) will be understood as an index that represents dimensionally the institutional capacity of the entities responsible for the integral management of the risk of responding orderly and efficiently to emergency situations that generate one or more threats determined [16]. It does not depend on the threats, and therefore it is calculated for each exposed population group (country, department, municipality, township, village) according to the generic Eq. (4):

$$ERC = \frac{\sum Pn.Wn}{Pn_{máx}} \tag{4}$$

where ERC is the extrinsic response capacity, Pn is the assessment of attributes of institutional capacity, and Wn is the weighting factor.

In accordance with the general functions of an incident command system (ICS) [22], the following descriptors and attributes for the ERC are proposed:

Planning: identification and characterization of risks, emergency plans, availability evacuation routes and shelters, simulation programming and coordination, and conformation and coordination of emergency committees.

Operation: optimal assistance distance, type and quality of route, population to be assisted, social care, medical assistance, and technical assistance in search and rescue.

Logistics: availability and management of supplies, communication system and early warning, transport, and facilities and equipment.

2.3 A new risk equation

As suggested, for the purposes of this study, comprehensive risk assessment is a process with a holistic, systemic, and environmental approach [16, 20], and, therefore, the definition of risk (R) refers to the probability that something harmful can happen in a certain environment or in a segment or element of it (ecosystem, public sector, economic sector, civil society).

In this context, with the help of the Excel tool and after successive trials with field information and conceptual and methodological approaches that avoided the null values for threats and vulnerabilities, a new expression was adjusted, as an index, for the determination of risk against volcanic threats, as shown in Eq. (5):

$$R = \text{Å}^{a}.V^{b} \tag{5}$$

where R is the risk index, Å is the intrinsic threat index, V is the vulnerability index, a is [b - c. ln (V)], b and c are the shape coefficients in the fit of the family of curves corresponding to the risk Eq. (5), as shown in **Figure 2**.

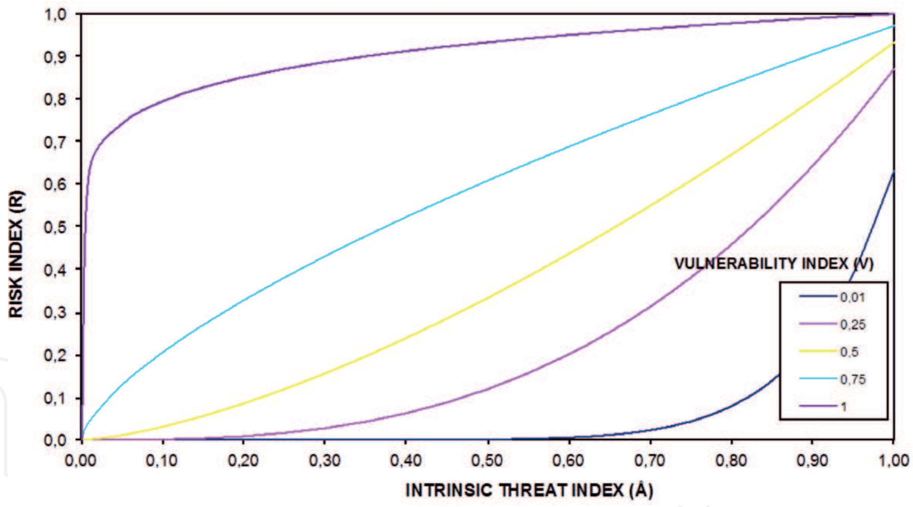

Figure 2.
Family of curves in the risk equation (R).

3. Methodological approach

The proposed methodological approach for comprehensive risk assessment involves two fundamental elements, the logical framework matrix and the process diagram, as explained below.

3.1 The logical framework matrix

Taking as a reference the logical framework matrix for systemic and integral evaluation of environmental impacts proposed in [20], the logical framework matrices are designed and defined for the integral evaluation of volcanic risk in the scenarios of the onset of crisis and eruption, which is shown in **Tables 3** and **4**.

3.2 The process diagram

Figure 3 schematizes the process diagram proposed for the integral evaluation of volcanic risk, which is consistent with the previously described conceptual framework.

To apply and develop this methodology is essential to have GIS tools [23], whose specific process includes a series of activities such as the collection and structuring

Exposed Elements	P [0-1]	CHARACTERIZATION OF THREATS AND VULNERABILITIES				Total risk on each exposed element
		Earthquakes		Landslides		
Ecosystem	P_e	$Å_s$ / V_{es}	$R_{es} = f(Å_s, V_{es})$	$Å_d$ / V_{ed}	$R_{ed} = f(Å_d, V_{ed})$	$R_e = \sum R_{ej} / \sum R_{(ej)máx}$
Constructed	P_c	$Å_s$ / V_{cs}	$R_{cs} = f(Å_s, V_{cs})$	$Å_d$ / V_{cd}	$R_{cd} = f(Å_d, V_{cd})$	$R_c = \sum R_{cj} / \sum R_{(cj)máx}$
Population	P_p	$Å_s$ / V_p	$R_{ps} = f(Å_s, V_p)$	$Å_d$ / V_p	$R_{pd} = f(Å_d, V_p)$	$R_p = \sum R_{pj} / \sum R_{(pj)máx}$
Total risk for each threat		$R_s = \sum (R_{is} \cdot P_i)$		$R_d = \sum (R_{id} \cdot P_i)$		$Rt = \sum (Ri \cdot Pi)$

Table 3.
Logical framework matrix for the integral risk assessment—start crisis scenario.

Exposed Elements	P [0-1]	CHARACTERIZATION OF THREATS AND VULNERABILITIES				Total risk on each exposed element
		Falls	Flows	Earthquakes	Landslides	
Ecosystem	P_e	$\frac{A_k}{V_{ek}}$ $R_{ek} = f(A_k, V_{ek})$	$\frac{A_f}{V_{ef}}$ $R_{ef} = f(A_f, V_{ef})$	$\frac{A_s}{V_{es}}$ $R_{es} = f(A_s, V_{es})$	$\frac{A_d}{V_{ed}}$ $R_{ed} = f(A_d, V_{ed})$	$R_e = \sum R_{ej} / \sum R_{(ej)máx}$
Constructed	P_c	$\frac{A_k}{V_{ck}}$ $R_{ck} = f(A_k, V_{ck})$	$\frac{A_f}{V_{cf}}$ $R_{cf} = f(A_f, V_{cf})$	$\frac{A_s}{V_{cs}}$ $R_{cs} = f(A_s, V_{cs})$	$\frac{A_d}{V_{cd}}$ $R_{cd} = f(A_d, V_{cd})$	$R_c = \sum R_{cj} / \sum R_{(cj)máx}$
Population	P_p	$\frac{A_k}{V_p}$ $R_{pk} = f(A_k, V_p)$	$\frac{A_f}{V_p}$ $R_{pf} = f(A_f, V_p)$	$\frac{A_s}{V_p}$ $R_{ps} = f(A_s, V_p)$	$\frac{A_d}{V_p}$ $R_{pd} = f(A_d, V_p)$	$R_p = \sum R_{pj} / \sum R_{(pj)máx}$
Total risk for each threat		$R_k = \sum (R_{ik} . P_i)$	$R_f = \sum (R_{if} . P_i)$	$R_s = \sum (R_{is} . P_i)$	$R_d = \sum (R_{id} . P_i)$	$Rt = \sum (Ri . Pi)$

Table 4.
Logical framework matrix for comprehensive risk assessment—eruption scenario.

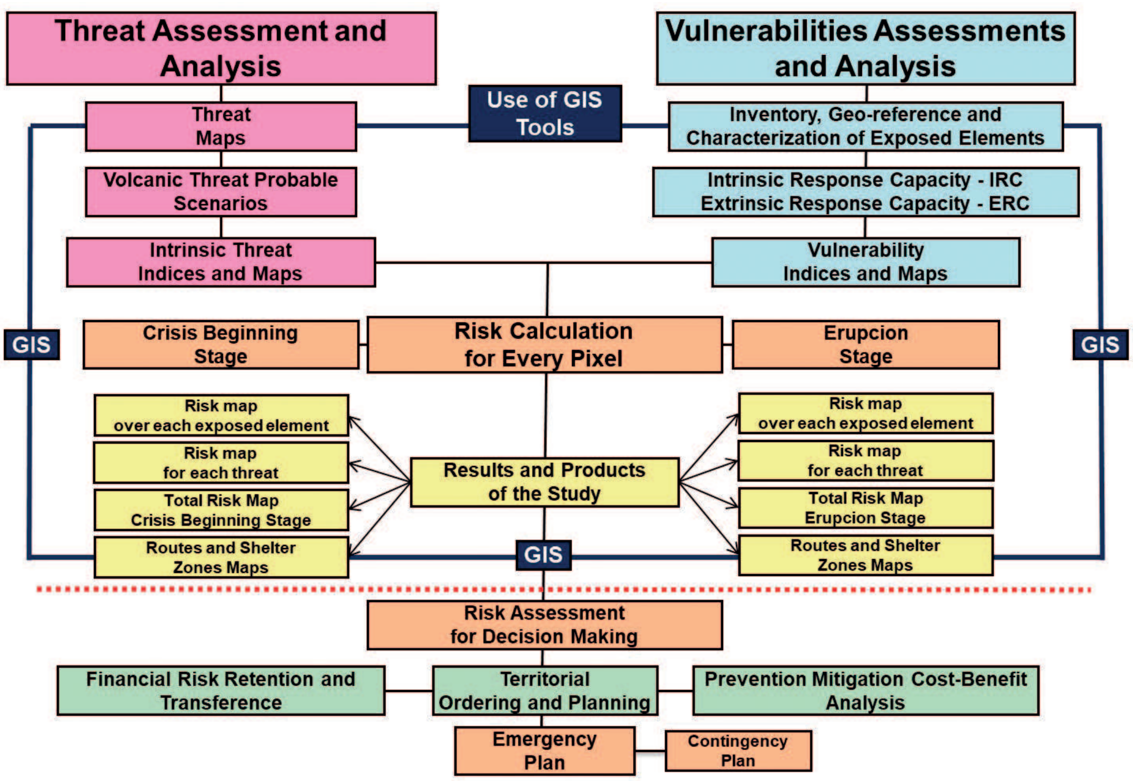

Figure 3.
Methodological diagram for the integral risk assessment.

of information; the alphanumeric and geospatial analysis with which it is possible to calculate the threat indexes, vulnerability, and risk at the level of each pixel of the study area; and finally the obtaining of products, such as risk maps for each analysis scenario.

What follows in this process diagram (after the dotted line in **Figure 3**) will be the risk assessment for decision-making in accordance with the retention and transfer of financial risk and with the cost-benefit analysis [24] that allows to define clear, precise, and consensual policy guidelines for land-use planning, as well as the corresponding emergency and contingency plans.

4. Case study: the Cerro Machín volcano

In the application of the conceptual and methodological approach previously exposed, the integral risk assessment is carried out in the Cerro Machín volcano, Colombia [16]. With this process, we obtain, for the scenarios of crisis initiation and eruption, the maps of total risk and the maps with the escape routes and zones of possible shelters for the transitory and/or definitive relocation of population and population centers, as shown below.

4.1 Total risk maps

According to the logical risk assessment framework, for each analysis scenario considered, the total risk maps are obtained by means of the weighted sum of the total risks on each exposed element, as shown in **Figure 4**.

According to the map in **Figure 4**, it can be seen in a general way that for the crisis initiation scenario, the highest total risk indexes are located in the areas near the volcanic building and in the valleys and slopes of the Toche and Bermellón rivers. For the eruption scenario, the high-risk indices are located in the areas exposed to the flows and landslides. The medium- to high-risk indexes are located in areas exposed to falls, characterized by the presence of crops and isolated rural housing.

4.2 Exit route maps and areas of possible hostels

The determination of escape routes and areas of possible temporary shelters and/or the final relocation of the population and population centers involves solving the following questions: When should evacuations take place? Who should be evacuated? Where and to where should they be evacuated? And so on. The answer

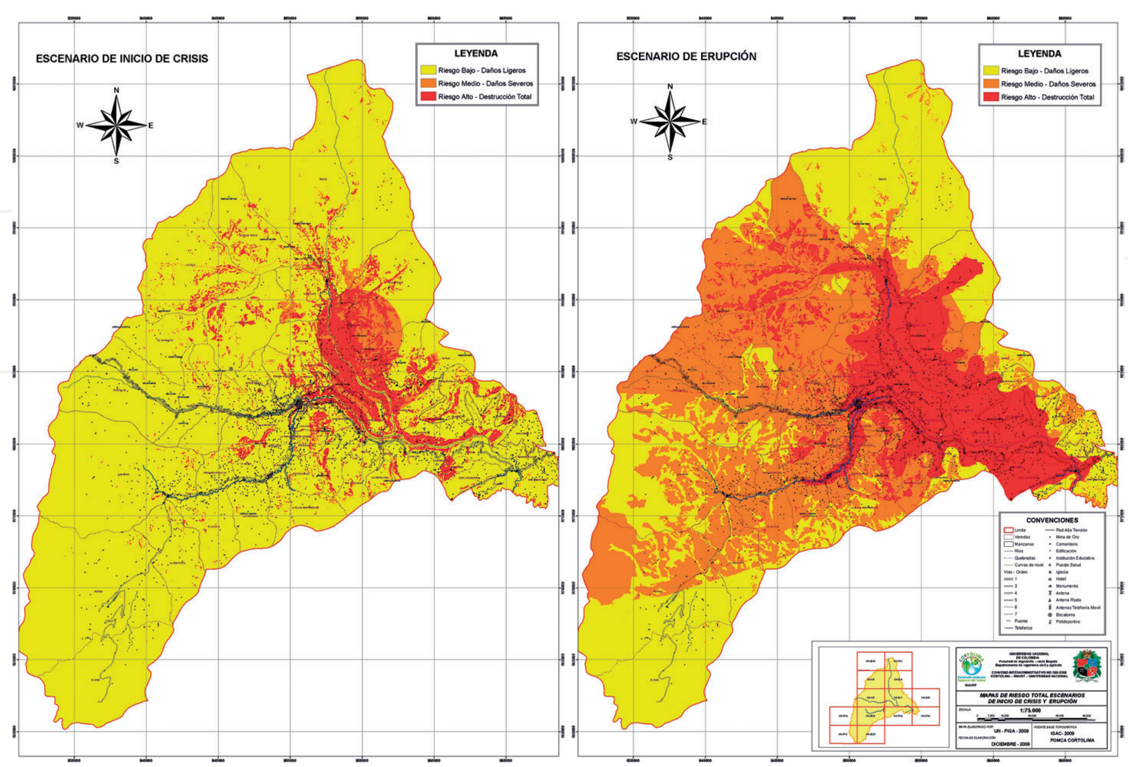

Figure 4.
Total risk duplex map—start of crisis and eruption scenarios.

to these questions constitutes a complex decision-making process that allows defining precise, clear, and consensual policy guidelines that guide, dynamize, and articulate a comprehensive risk management that adequately involves both the processes of comprehensive risk assessment and the formulation of emergency, contingency, and mitigation plans that guarantee efficient and effective risk management.

This process of making political, economic, administrative, logistical, social, environmental and technical decisions can be easily carried out if you have the right information and tools. This analysis should consider adjustments in land use planning, in the retention and transfer of financial risk, and of course, in cost-benefit analyzes for the prevention and mitigation of risk.

Taking into consideration the total risk maps for the two analyzed analysis scenarios, the maps are generated where the escape routes and areas of possible shelters for transient and/or definitive relocation of population and population centers are defined, as they are presented in duplex manner in **Figure 5**.

According to the above, some preliminary aspects to be considered in the process of progressive evacuation of risk areas are described below.

Pre-crisis scenario: according to [17], this scenario corresponds to the current situation of the volcano and may last from several to hundreds of years, in which the threats do not materialize. It is characterized by strong emanations of gases and by the eventual seismicity of the volcanic building that can cause some important landslides in the most susceptible areas and get to affect the nearest inhabitants and some communication routes. Due to the characteristics of this scenario and in light of the risk study carried out, one should now think of a definitive relocation strategy for the population settled in the high-risk area and begin immediately with the active participation of the community and the tasks of review, validation, and testing of emergency plans.

Start crisis scenario: according to [17], this scenario can last from hours to weeks prior to an imminent eruption and is characterized by the increase of seismicity, gas emissions, and the possible collapse of the south western side of the volcanic building, causing the damming of the Toche river and landslides in the areas near the

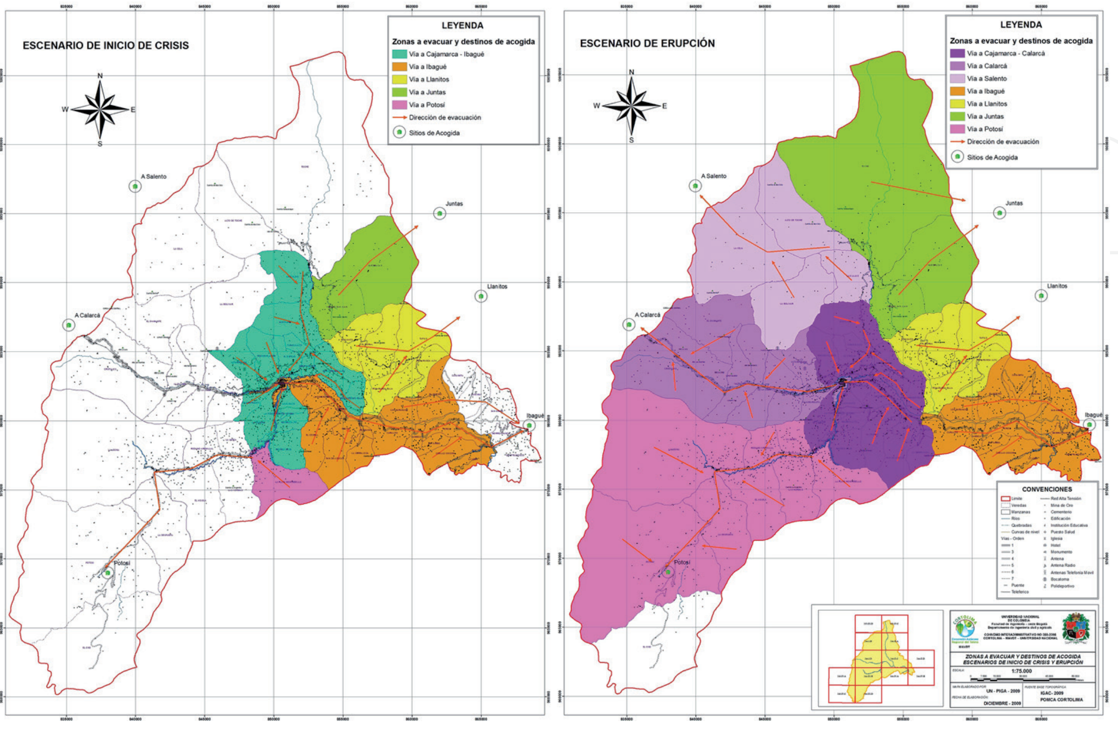

Figure 5.
Duplex map of escape routes and areas of possible hostels—scenarios for the initiation of crises and eruption.

volcano. According to the total risk map in the crisis start scenario, the lands that comprise the volcanic building, approximately five kilometers around the volcanic cone, are at high risk. Consequently, in this scenario, all efforts and contingency plans for the evacuation of people to save the greatest number of lives could still be safely implemented.

Eruption scenario: according to [17], this scenario can last from days to weeks, it includes the phases of minor eruptions, blast, and principal, and all threats are materialized, and the area of affectation is considerable. According to the total map of risks in eruption scenario (**Figure 5**), a large part of the study area that involves, among other elements, the population centers of Cajamarca, Anaime, Toche, Tapias, and Coello-Cocora, as well as the Pan-American Highway in the section between Ibagué and Cajamarca, are at high risk. Consequently, it would be expected that the occurrence of this scenario will ensure that the populations located in high risk areas have already been evacuated and relocated previously according to the map of escape routes and areas of possible hostels. Likewise, it would be expected that the populations located in areas of medium to low risk have already been prepared to start the evacuation processes to the recommended sites.

5. Conclusions and recommendations

The study establishes the bases of a new conceptual and methodological framework for the integral risk assessment, which, in addition to guiding the development of the study, allows the generation of information processing and analysis tools to make it possible.

According to the total risk maps for each analysis scenario, it is evident that in the event of an eruption of the Cerro Machín volcano, the population centers of Cajamarca, Anaime, Toche, Tapias, and Coello-Cocora, as well as the Pan-American Highway in the stretch between Ibagué and Cajamarca, would be seriously affected.

According to the map of escape routes and areas of possible hostels, it is ratified as an adequate site to relocate the populations of Cajamarca and Anaime to the Potosí sector, provided that it is complemented with the layout, design, and construction of a new road that communicates from Ibagué to Potosí and from there to Quindío, not to leave these populations isolated.

According to the map of total risks and in compliance with the precautionary principle, it is recommended to continue with the processes of education and preparation of the population for the emergency, indicating their escape routes and temporary and/or definitive shelter sites. It is considered pertinent to start already (immediately) the design of a comprehensive prevention strategy, which, on the one hand, orients the processes of relocation of the aforementioned population centers and, on the other, initiates the design, layout, and construction of a new route or route alternate that gives operational redundancy to the current Pan-American route.

It is recommended to convert the entire surrounding area to the Cerro Machín volcano in a large protected area attached to the national system of natural parks, which guarantees an ordering and territorial management more appropriate to the risks involved and its great ecotouristic potential. This option will allow, in principle, the reorientation of resources for the maintenance of access roads, and, in passing, the strengthening of risk management capacity. In the future, it will allow the development of low impact ecotourism activities, through hostels, thermal pools, restaurants, ecological trails, etc. as well as the construction of a cable car that facilitates rapid access from Cajamarca to the hill of San Lorenzo and from there to the Machín volcano crater.

It is evident that the integral evaluation of the risk is a determining factor in the processes of territorial ordering and therefore it is suggested the revision and adjustment to all the territorial planning plans that have not involved this factor, in a priority way in those watersheds and populated centers with obvious natural threats by volcanism, mass removal, torrential floods, avalanches, floods, forest fires, etc.

Finally, it is suggested to test and calibrate the model developed in the risk assessment of other volcanoes in the country.

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Author details

Leonel Vega
Universidad Nacional de Colombia, Bogotá, Colombia

*Address all correspondence to: lvegamora@unal.edu.co

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