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ORIGINAL PAPER

Multi-hazard model for developing countries

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Abstract Disaster risk assessment related to natural events has generally been carried out separately by specialists in each area of earth sciences, which has two negative consequences: Firstly, results of investigations are presented in different formats, mainly maps, which differ significantly from each other in aspects such as scale, symbols and units; secondly, it is common for an area or territory to contain several hazards that can potentially interact with each other, generating cascade effects or synergies. While some authors have proposed a multi-hazard analysis framework based on the use of probabilities, the quality and quantity of data required for this approach are rarely available in developing countries. Qualitative methods, on the other hand, have traditionally been limited to overlapping maps, without considering possible spatial interactions. Given the importance of integrated assessment of natural hazards for land use planning and risk management, this article proposes a heuristic multi-hazard model appropriate for developing countries, based on a standardization of classifications and a spatial interaction matrix between hazards. The model can be adjusted to be applied at different scales and in different territories; to demonstrate its versatility, it is applied to the municipality of Poás, Costa Rica, a territory with multiple natural hazards.

Keywords Multi-hazard · Risk management · Land use planning · Municipality of Poás, Costa Rica

1 Introduction

In developing countries, it is common to find natural, environmental and socioeconomic conditions conducive to the occurrence of disasters related to natural hazards. In the Central American region, for instance, there are earthquakes; floods caused by the passage

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of cyclones, tropical storms and cold fronts; landslides; various types of volcanic hazards such as ash fall, pyroclastic flows and ballistic projection of materials; and storm surge, tsunamis, among other factors.

The natural hazards often occur in territories characterized by high vulnerability as a result of high rates of poverty, illiteracy, social exclusion and environmental degradation.

For both management of current disaster risks and to reduce future exposure to risks (risk prospecting), a model is required for assessing natural hazards in multi-hazard areas that is designed to be used in land use planning by local governments in developing countries. It is therefore necessary to have a model to assess different hazards present in a territory from a spatial perspective, considering their overlaps and possible interactions due their overlaps.

Given the scarcity of available information on natural hazards in developing countries, as well as the need to integrate information about each of these hazards in specific territories (local governments), a heuristic model is proposed. The municipality of Poás, one of the 81 political divisions of Costa Rica, has been chosen as a test case (Fig. 1). Its geographic position and physiography subject it to natural hazards such as volcanism, floods, landslides and seismicity. In addition, the municipality is preparing a land use plan, which requires information to support decision making for the management of disaster risks.

1.1 Principal characteristics of the municipality of Poás

The municipality of Poás is located in the Central Valley of Costa Rica, Central America, in the province of Alajuela; it has an area of 73.84 km^2 and a population of 29,199 people, according to the 2011 census (INEC 2012). It has an elongated shape that begins with a wedge of the main crater of the Poás volcano at 2700 masl, and extends from the NNE to SSW until it reaches the confluence of the Prendas and Poás rivers at 650 masl (Fig. 1).

The Poás volcano is a complex stratovolcano with an irregular subconical shape (Alvarado 2000), whose current eruptive focus is located within a volcano-tectonic fracture with a north–south orientation. The volcano has been moderately active on an almost continuous basis, with gas emissions and occasional phreatic eruptions, and has also produced mild Vulcanian and Strombolian explosions (Prosser and Carr 1987).

Four geological formations are found within the study area. From north to south, these formations are described by Ruiz et al. (2010) as: Unidad Cima Poás, which mainly consists of basaltic lava and andesites; Unidad Poasito which consists of lava flows attributed to volcanism in fissures on the south side of the volcano; Unidad Achiote, which is a set of andesitic and basaltic lava flows; and the Tiribí formation, which is made up of a layer of basal pumice with a maximum thickness of 3 m, followed by a deposit of ignimbrites with different facies.

Several faults pass through the study area, related to the cuspidal structure of the Poás volcano; this is a system of normal faults around the northeast and southwest areas of the cuspidal zone, which are easily detected because of their steep escarpments. There is also the Alajuela fault, a reverse fault propagation which has an orientation varying between E-W and WNW-ESE (Montero et al. 2010) and is located to the south of the study area.

The area's geomorphology may be divided into three large units. The first is the summit of the Poás volcano, a blunt prominence where the volcano's crater is located, as well as steep escarpments of normal faults. The second section extends over a field with steep slopes containing the headwaters of micro-watersheds and steep river valleys, finally

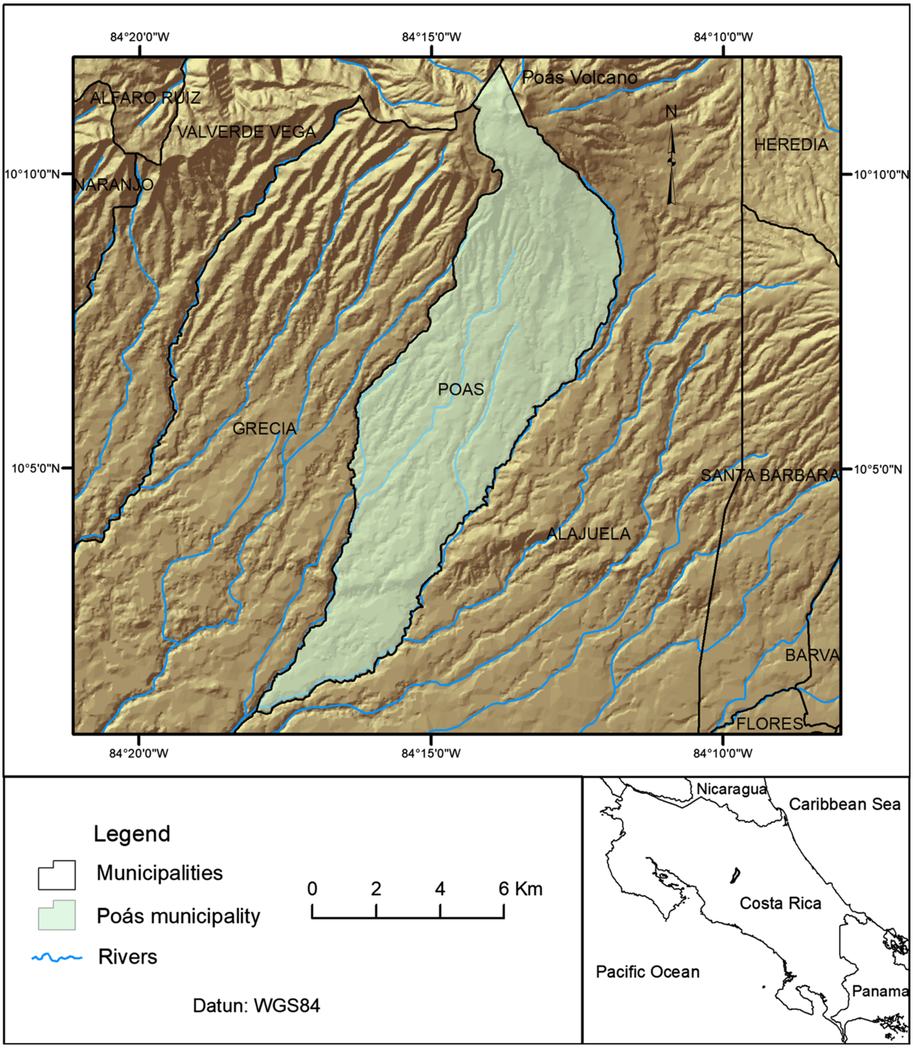


Fig. 1 Municipality of Poás, Alajuela, Costa Rica, 2017

reaching the third unit, an undulating field surrounded by narrows in the southern extreme of the municipality.

The zone has two marked climate zones: higher areas have a temperate wet climate with annual temperature averages between 15 and 18 °C, are constantly cloudy and have a relative humidity of 90%. There is no distinct dry season, and annual rainfall ranges between 5000 and 6000 mm in the volcanic structure. Lower areas have a tropical climate with a dry season that lasts between 3 and 4 months. Average relative humidity is approximately 85% during the period of peak rainfall and up to 65% in the dry season. Average temperatures range between 19 and 23 °C.

2 Multi-hazard risk analysis

Evaluating each hazard separately to calculate estimated losses for different degrees of danger or probabilities of occurrence (risk scenarios) is a common practice in risk studies. The multi-hazard risk approach considers different types of hazards and vulnerabilities and combines findings into layers of individual risks, making it possible to consider all the risks present in specific areas (Komendantova et al. 2014). This author also indicates that three software programs are available at the international level that provide singular risk assessments for several natural hazards in specific areas: HAZUS for hurricanes, earthquakes and floods (in the USA); RiskScape for ash fall, floods, tsunamis, landslides, storms and earthquakes (in New Zealand); and CAPRA, for hurricanes, extreme rainfall, landslides, floods, earthquakes, tsunamis and volcanic hazards (in Central America).

However, the construction of risk scenarios without an integrated framework may tend to underestimate total risk, since it does not consider the spatiotemporal overlap of hazards, and the possibility of synergies and cascade effects. Perales and Cantarero (2010) criticize the existing methodologies for evaluating natural hazards in multi-hazard environments, and conclude that:

- Risk mapping is currently carried out in different disciplines, each of which focuses on its own areas of study.
- In most methodologies, integration attempts are limited to the spatial overlap of hazards, and mapping is used as an accessory element in these efforts.
- Cartographic standards should be established to guide the mapping of hazards and risks emphasizing on land use planning.
- Different hazards present in the same space should be considered, as well as possible chain effects.

An approach focused on multi-risk analysis has recently emerged. This approach considers risk as a product of multiple sources and multiple vulnerabilities that coincide in time and space and includes interactions between hazards and cascade effects between events (Komendantova et al. 2014). In practice however, available integrated frameworks are based only on general postulates and examples with a limited number of hazards (Delmonaco et al. 2007; Fleischhauer et al. 2006; Perales and Cantarero 2010).

Kappes et al. (2012) consider that multi-risk analysis includes three stages: (a) multi-hazard analysis, (b) vulnerability of elements at risk for multiple hazards and (c) multi-hazard risk. The first stage refers to the implementation of methodologies or approaches that help to assess and map the potential for occurrence of various types of natural hazards in a given area. The second refers to a common framework for assessing individual vulnerabilities that allows for a joint analysis approach, considering the spatiotemporal relationships that alter vulnerability. The last stage consists of the process of combining results of the two previous stages, a process that these authors consider is facilitated by the fact that hazards are not expressed in specific units but rather as expected losses such as the annual probability of loss of lives. This advantage will exist as long as the risk calculation has been standardized from the beginning of the analysis, which makes it possible to combine different results in the calculation of the total multi-hazard risk.

For the first step, multi-hazard analysis, Marzocchi et al. (2012) propose a probabilistic approach, which allows the consideration of events occurring at the same time and events that result from the occurrence of other events (Fig. 2). They further note that in this

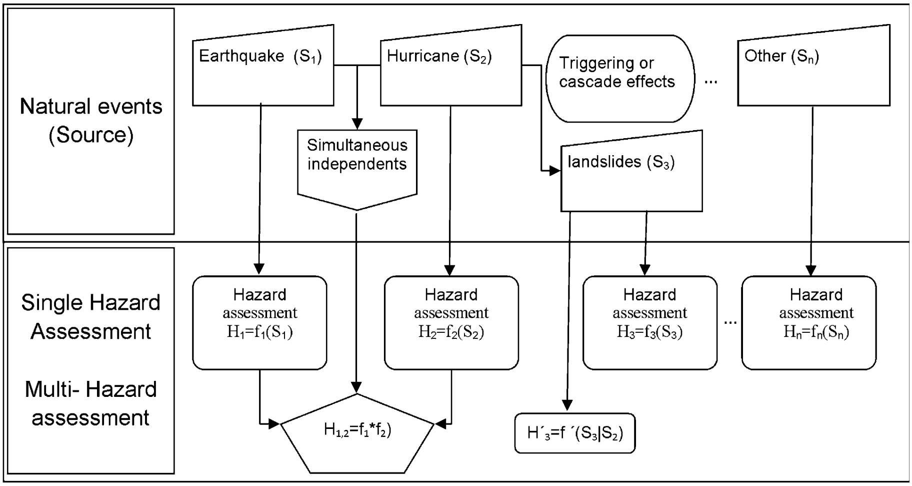


Fig. 2 Descriptive diagram of part of the proposed multi-risk probabilistic assessment model of Marzocchi et al. (2012)

approach the first step should be to define the spatiotemporal analysis, and propose a scenario technique combined with the use of a probability tree using a Bayesian approach.

This probabilistic approach is based on certain assumptions, such as the existence of an updated and sufficiently long record to be able to characterize the behavior of natural events statistically. However, this assumption is rarely fulfilled in developing countries, as is the case in Central America. Additionally, this approach assumes that the past behavior of an event will be maintained in the future, which is questionable if one considers, on the one hand, global climate change and, on the other hand, rapid urban expansion and changes in land use, factors that definitely alter natural processes, in particular those related to hydrological cycles and hillside processes.

An alternative approach for considering different events in a single integrated framework is standardization, which can be carried out through the development of indices (a semiquantitative approach) or by a classification of hazards (a qualitative approach) (Kappes et al. 2012).

Hazard indices are developed by assigning continuous standardized values to the parameters used to calculate each hazard (which are otherwise not directly comparable), resulting in a pseudo-quantification of the differences between hazards. These indices are calculated using formulas that consider related factors such as frequency, intensity and extent of hazards. The index value allows the numerical (semiquantitative) comparison of hazards and not directly of the parameters that are used in their calculation. For mapping, index values are grouped and presented on a qualitative scale. This is the method adopted in Natural Disaster Hotspots (Dilley et al. 2005).

Standardization of classifications is the technique most frequently used to compare different hazards, where intensity or frequency thresholds are defined to classify the respective hazards in a predefined number of classes. This makes it possible to compare classes independently of the hazards that generated them—for example, the “very high” classes of seismicity and floods represent the same level of severity although the processes and their effects are different (Kappes et al. 2012).

An representative example of the application of this method was the Applied multi Risk Mapping of Natural Hazards for Impact Assessment (ARMONIA) project, which proposed a regional hazard intensity classification scheme in three categories for spatial planning purposes (low, medium and high intensity) (Delmonaco et al. 2007). The Swiss version (the Swiss Guide for the analysis and evaluation of natural hazards) combines intensities and frequencies to establish hazard categories, just as Barrantes et al. (2011) did in the case of the Irazú Volcano in Costa Rica. Finally, the overlaps of hazards in the same areas are evaluated and the highest individual value will be adopted as the multi-hazard value for each particular area (Heinimann et al. 1998).

After an extensive review of methodologies and applications of multi-risk assessment, Kappes et al. (2012) concluded that classification and indexing approaches are a valuable tool to address the problem of characterizing individual hazards and their integration, even though their usefulness is limited to the specific purpose or target group for which they are developed. These same authors explain that an approach that considers or quantifies the possible consequences in terms of probable losses is more promising, but this implies a quantitative approach.

In the case of risk analysis for land use planning, the Andean Community Disaster Prevention Project (PREDECAN 2009) mentions the gradual nature of knowledge acquisition, which is directly related to the approaches and scales used in each stage. These aspects characterize the scope and resolution of studies on natural events, following a sequence that begins with exploratory activities, continues with rough estimates and progressively deepens to achieve high levels of resolution and analytical refinement.

While detailed studies are preferable, the availability of economic and human resources, and data on each hazard are the factors that determine the level of detail that is possible at any given time. Due to the scarcity of available records and studies on natural hazards in developing countries, this investigation will use a standardization of classifications approach based on heuristic methods. The methodology presented in this article was applied in the of Poás, Costa Rica, as a test case.

3 Methodology

The proposed natural multi-hazard model is based on the spatial overlapping of the standardized assessment of individual hazards and relies on the following principles:

- Each natural hazard is spatially represented by a standardized class value, ranging from 1 to 5, as an ordinal scale representing categories of hazard severity (very low, low, moderate, high and very high), on the assumption that classes can be compared to each other regardless of the type of hazard in question.
- The importance of each hazard will decrease in proportion to the frequency with which events reoccur, so that the value assumed by each particular hazard can be reduced (weighted) when events are widely separated in time.
- Spatially overlapping hazards can interact with each other, amplifying their effects, and such interactions can be represented by a matrix of spatial interactions.
- The multi-hazard value that represents each minimum spatial unit will correspond to the highest hazard class value present in that spatial unit.
- To establish a useful spatial analysis framework for subsequent incorporation in territorial planning, a work scale should be predefined whose level of detail will be

determined by the detail of the information source available and the purpose for which it was created.

The steps for calculating the model are summarized below:

1. Standardize hazard studies using a qualitative scale of five categories. This implies that the hazard studies to be included should be divided into zones at appropriate spatial scales. If there are no previous zoning studies at appropriate scales, qualitative methods can be used that classify hazard levels into five categories (very low, low, moderate, high and very high).
2. Reduce the hazard category for each hazard in relation to its temporal frequency. To do so, events must be classified into three groups according to their temporal frequency, and each group is assigned a modifying factor that will be used to decrease its importance in the calculation of the multi-hazard index. The proposed moderation values are based on the fact that a home has a useful life of 50 years.
3. Assign a weight to the spatial interaction between overlapping hazards for hazard values equal to or greater than 3. To establish the interaction between natural hazards, consider the possible synergies between them by means of a matrix of spatial interactions (Table 1). The interaction weights are based on an arbitrary scale of 0–1, where 0 represents absence of interaction between events and 1 the maximum synergy.

To complete the matrix was developed an ordinal scale applicable to all combinations of natural hazards, which will guide the allocation of weights by spatial interaction. Each interaction category is represented by a value, and to maintain the incremental logic of the scale and to be able to adapt it to the conditions of each territory in which it will be applied, in each category the possible values fall within a range of values that represent the strength of spatial interactions. The classes of the ordinal scale are as follows:

A. *No spatial interaction* events that in general are not related to each other despite being able to occur in the same area.
B. *Sum of negative effects* events that tend to have a temporal correlation, but whose combined effect does not exceed the sum of their individual effects, as in the case of falling volcanic bombs and ash.
C. *Transfer of mass and/or energy from one event to another* when one event is transformed into another or adds mass or energy to another, as in the case of landslides that are transformed into debris flows.
D. *Trigger or cascade effects* when one hazard can trigger another, such as when an earthquake triggers one or more landslides.

Table 1 Matrix of potential interactions between natural hazards

	Hazard 1	Hazard 1	Hazard 1	Hazard 1	…	Hazard 1
Hazard 1						
Hazard 1						
Hazard 1						
Hazard 1						
…						
Hazard 1						

E. *Conditional effect* when one hazard depends on the occurrence of another, such as liquefaction of the ground depending on the occurrence of a strong earthquake.

Expert criteria are used to establish the most appropriate weight for each geographic context. Consultation can be carried out individually or in groups. The weights that represent expert criteria (column 3 in Table 2) will be placed in the spatial interactions matrix according to the type of interaction that is present between each row/column (Table 1).

4. Calculate the multi-hazard value for each minimum spatial unit, by assigning the highest of the overlapping individual hazard values in a minimal spatial unit to the multi-hazard value, once steps 2 and 3 are carried out. The final result will correspond to the standard scale of values from 1 to 5 (very low, low, moderate, high and very high).

The conceptual model for the multi-hazard assessment is presented in Fig. 3. The hazards that are present in the area in which the model is applied are represented by circles in the figure; the importance of each individual hazard remains the same or decreases according to its associated frequency class, and in the case of individual hazards with values equal to or greater than 3, a weight is added to account for spatial interaction according to the spatial interactions matrix, it is represented by gray tones in Fig. 3.

The mathematical formulation of the model for its application under a raster spatial data model (pixels) is presented in the following formula (Eq. 1):

$$\mathrm{MHV} = [(\mathrm{IHV_i} \times \mathrm{MF}_i)]\max + \sum_{\mathrm{IHV_i} \geq 3}^{5} \mathrm{HW}_{ij} \tag{1}$$

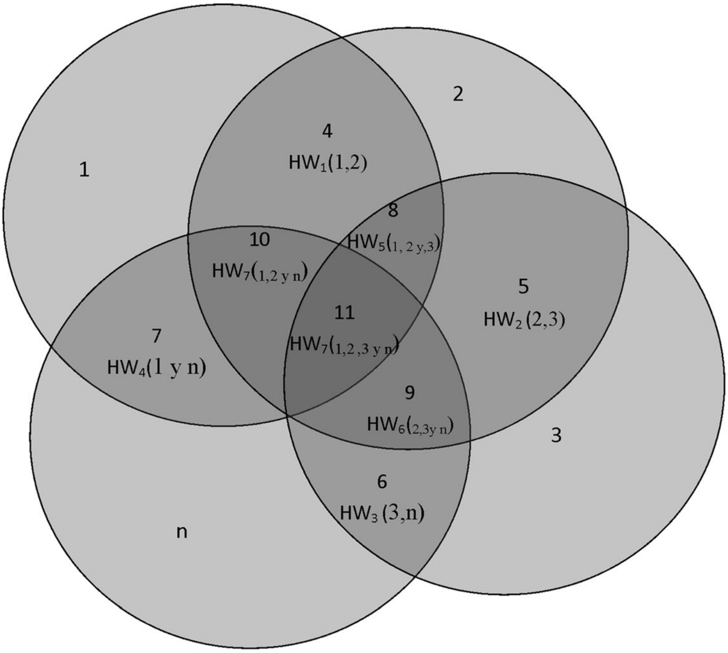
where MHV is multi-hazard value; $\mathrm{IHV_i}$, individual natural hazard standardized value (from 1 to 5); MF_i, moderation factor of the hazard i according to its relative frequency of recurrence; $\mathrm{HW_{ij}}$, spatial interaction weight between hazards i and j; *max*, value of the highest individual natural hazard per pixel.

When the resulting value is not an integer, it is rounded up if it is greater than 0.5. If the result has a value greater than 5, it will be assigned the value of 5 by default, since this value represents the maximum possible hazard.

The municipality of Poás, Costa Rica was selected as a test case for implementing the methodology. In this case, ten natural hazards were zoned and standardized: landslides, debris flows, rapid flooding, seismic shock, ash fall, ballistic projection of pyroclasts, volcanic gases, pyroclastic flows and waves and lava flows. The details of the standardization by classification of each of these hazards are presented in Barrantes (2015).

Table 2 Types of spatial interactions and range of adjustment to establish weight by possible spatial interactions between individual hazards

Possible spatial interaction between hazards	Reference interval	Expert criterion
No spatial interaction	0	
Total of negative effects	0–0.3	
Transfer of mass and/or energy from one event to another	0.3–0.6	
Trigger effects	0.6–0.9	
Conditional effect	0.9–1	



1 $MH_1 = (H_1 \ast M_h)$

2 $MH_2 = (H_2 \ast M_m)$

3 $MH_3 = (H_3 \ast M_l)$

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n $MH_n = (H_n \ast M_n)$

4 $MH_4 = \mathrm{MAX}\ (MH_1, MH_2) + HW_1$

5 $MH_5 = \mathrm{MAX}\ (MH_1, MH_3) + HW_2$

6 $MH_6 = \mathrm{MAX}\ (MH_3, MH_n) + HW_3$

7 $MH_7 = \mathrm{MAX}\ (MH_1, MH_n) + HW_4$

8 $MH_8 = \mathrm{MAX}\ (MH_1, MH_2, MH_3) + HW_5\ (\mathrm{SUM}(HW_1, HW_2))$

9 $MH_9 = \mathrm{MAX}\ (MH_2, MH_3, \ldots MH_n) + HW_6\ (\mathrm{SUM}(HW_2, HW_3))$

10 $MH_{10} = \mathrm{MAX}\ (MH_1, MH_2, \ldots MH_n) + HW_7\ (\mathrm{SUM}(HW_1, HW_4))$

11 $MH_{11} = \mathrm{MAX}\ (MH_1, MH_2,, MH_3, \ldots MH_n) + HW_7\ (\mathrm{SUM}(HW_1, HW_2, HW_3, HW_4))$

Fig. 3 Conceptual model for multi-hazards assessment of natural. Circles represent the spatial extent of individual hazards (1,2,3,n) and areas with gray tones spatial interaction between hazards (4, 5, 6, 7, 8, 9, 10, 11)

The steps followed for the application of the methodology are listed below:

1. Assignment of a moderation factor. Once the individual natural hazard zones were standardized in the Poás area using the same spatial framework, hazards are grouped into frequency classes for the application of a moderation factor; results are shown in Table 3.

Table 3 Moderation factor assigned to each hazard type

Temporal frequency	Event type	Moderation factor
High	Landslides	1
	Rapid flooding	
Moderate	Debris flows	
	Seismic shocks	0.5
	Volcanic gases	
Low	Ballistic projection of pyroclasts	
	Ash falls	
	Pyroclastic flows	0.25
	Pyroclastic waves	
	Lava flows	

2. Consider possible interactions between hazards. The spatial interaction weights required to construct the Poás interaction matrix were defined based on expert judgment, and the results obtained are shown in Table 4.
3. Calculate the multi-hazard value for each pixel within the municipality. The proposed formula for a raster data model (Eq. 1) was implemented using the ArcGIS model builder tool, which can be replicated for application of the model in other territories of developing countries.

4 Results

Results of application of the natural multi-hazard methodology are shown in Fig. 4, which shows that areas with the greatest natural hazard are located mainly in the north and central parts of the municipality, especially near the summit of the Poás volcano, in the head of watersheds, on the slopes of narrow valleys and on the anticline of the Alajuela Fault. The factors that explain this distribution are the irregularity of the terrain (steep slopes) and the higher humidity in the middle and upper sections of the municipality. These factors favor a high susceptibility to landslides and debris flows, which is increased in the central and northern part of the municipality by possible spatial interactions with other hazards, including volcanism and seismicity.

In the southern section of the municipality, on the other hand, an area classified as having a moderate multi-hazard ranking extends along the steep slopes of the valleys. This extension is influenced by a reduction of humidity with lower altitudes, as well as by the remoteness of active volcanic and seismic sources.

The areas with a low multi-hazard rankings are located to the center and south of the municipality and correspond to undulating fields or convex slopes, which mostly coincide with morphologies derived from old lava flows, interfluves, or deposits of old alluvial fans. Again, the distance from volcanic and seismic sources, as well as less inclined slopes and lower humidity, helps to explain this distribution.

Application of the model in the municipality of Poás shows that the areas categorized as having very high and high hazard categories represent 58% of the municipality's total area (Fig. 5).

Table 4 Matrix with the weights given to the possible interaction between natural hazards

	Landslides	Debris flows	Rapid flooding	Ballistic projection of pyroclasts	Ash falls	Volcanic gases	Pyroclastic flows	Pyroclastic waves	Seismic shocks	Lava flows
Landslides										
Debris flows	0.5									
Rapid flooding	0.5	0.5								
Ballistic projection of pyroclasts	0	0	0							
Ash falls	0.5	0.5	0.25	0.25						
Volcanic gases	0.25	0	0	0.25	0.25					
Pyroclastic flows	0	0	0.25	0.25	0.25	0.5				
Pyroclastic waves	0	0.5	0.25	0.25	0.25	0.5	0.5			
Seismic shocks	0.75	0.75	0	0	0	0	0	0.25		
Lava Flows	0	0	0	0	0	0	0.25	0	0	

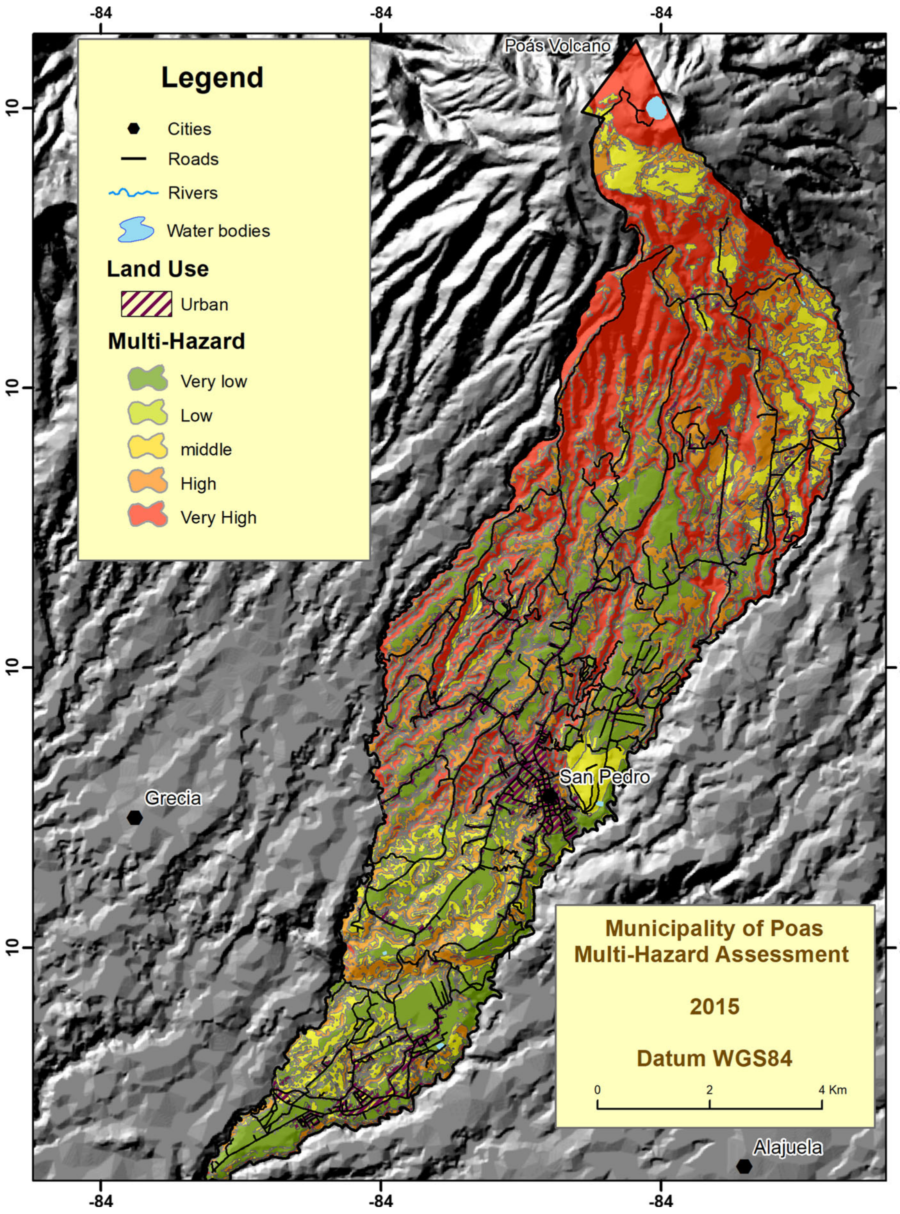

Fig. 4 Multi-hazard model applied in the municipality of Poás

5 Discussion of results

Application of the model resulted in a useful product for land use planning, and the model itself is applicable to countries with short and poor records of natural hazards and disasters. The multi-hazard assessment carried out in the case of the municipality of Poás, Costa Rica, represents the starting point for a study of physical vulnerability (exposure). By

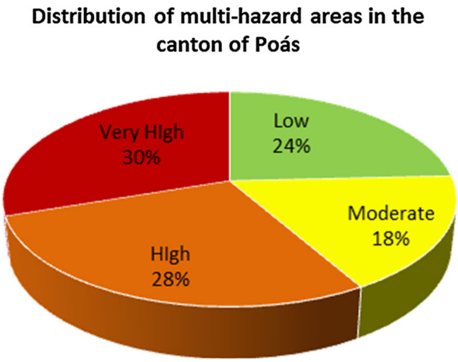

Fig. 5 Percentage distribution of areas by natural multi-hazards classifications in the municipality of Poás

overlapping the use of urban soils, it is possible to deduce, in a preliminary fashion, that the main populated centers of the municipality are adequately located in low and moderate multi-hazard natural zones (Fig. 4). In contrast, the settlements of Bajos del Tigre and La Santa are located in very high multi-hazard zones, and El Jaúl and Las Cabras are located in high multi-hazard zones, but they are dispersed linear settlements with low population density.

The proposed methodology allows identifying sites that require detailed studies to determine their exposure to risk (such as slope stability studies or flood height and speed calculations, as well as studies of technical, economic, social and environmental vulnerability) which would support proposals for risk prevention, mitigation or preparation.

Likewise, results of the model can be used for risk prospecting, for example by superimposing the results on proposed land use zoning in the regulatory plans (land use planning) to assess whether risks would grow with proposed increases in urban areas. If this situation is encountered, it would be possible to restrict land use in very high and high hazard areas (reorienting urban expansion) and to promote the application of mitigation measures (through appropriate regulations) where the hazard is moderate.

6 Conclusions

A multi-hazard model appropriate for application in territories with multiple hazards and with limited data was designed. The algorithm used complements the spatial overlap of the values of each hazard with an estimate of the interaction potential between different hazards and their temporal frequency.

Problems with records of recurrences of hazards that only cover short periods of time and inaccurate data were accommodated by assigning a moderation factor which reduces the value (class) of the hazard as a function of the periodicity with which it occurs in a given area.

A qualitative procedure was developed to incorporate spatial interactions between individual natural hazards through a matrix of spatial interactions, which makes it possible to increase the class value of the most serious hazard when an interaction between different hazards occurs in the same basic spatial unit.

A model was designed that supports decision making for land use planning in terms of risk management. Given natural multi-hazard levels in different zones, it is possible to orient urban land use toward safer areas and discourage the intensive use of the most dangerous areas by incorporating these results into land use plans.

It was found that 58% of the total area of the municipality of Poás was classified as being in a very high or high multiple natural hazard zones, in which risks of landslides and debris flows may be aggravated by the occurrence of other hazards such as earthquakes, ash fall or acid rain. Likewise, 18% of the area of the municipality was classified as having moderate exposure to multiple natural hazards, corresponding to zones located on moderate slopes near the top of the volcanic building or the Angel Fault, or on steep slopes located on the sides of valleys in the southern section of the municipality. Finally, 24% of the territory is in a low multiple natural hazard zone located in the center and south of the municipality, corresponding to areas of less inclined slopes far from seismic and volcanic sources.

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