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Landslide risk index map at the municipal scale for Costa Rica

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ABSTRACT

Landslides are a common natural hazard worldwide with greater socioeconomic impacts in developing and tropical countries. In Central America and Costa Rica, this phenomenon is mainly triggered by seismicity and extraordinary rainfall. In order to portray the damaging landslides, that caused human and material losses in Costa Rica, DesInventar disaster database was used to analyze damaging landslides reports from 1970 to 2018. Moreover, different generalized linear models (GLM) were performed to analyze the landslide hazard, vulnerability and risk in all the municipalities of the country. An Akaike Information Criterion (AIC) backward selection was used to contrast and determine the best hazard and vulnerability models. From a total of ten variables, terrain ruggedness index, 5 year intensity-duration-frequency precipitation curves and earthquakes distribution determined the landslide hazard. Otherwise, population, municipality area and Social Development Index are the most suitable variables to explain the landslide vulnerability. Subsequently, the multiplication between alternative landslide hazard and vulnerability indexes produced the risk index. Consequently, the highest risk values were obtained for large and rural municipalities (Pérez Zeledón, San Carlos, and Turrialba) as well as for densely populated and urban units (Alajuela, Desamparados, and Cartago. Results are critical for disaster risk reduction public institutions and academic stakeholders. Therefore, this methodology could be an interesting opportunity for different tropical and developing countries to achieve national or regional analyses of the most important risk component in each municipality and implement risk reduction strategies adapted for each municipality characteristics.

1. Introduction

Landslides occur globally but some regions are hotspots due to their geophysical dynamic such as tropical mountains [1]. Fatalities related to landslides are greater in tropical and developing countries [2]. Generally, natural disasters in developing countries have the most severe impact on economic growth per capita [3,4]. National landslide hazard, vulnerability or risk indexes or catalogues have already been carried out in countries such as Cuba [5], Georgia [6], Germany [7], Great Britain [8], Mexico [9], Portugal [10] and Turkey [11].

Risk management strategies principal goals are to diminish risk and losses [4]. A landslide risk assessment can be accomplished applying integrated economic, structural, cultural, legal, social, health, environmental, technological, political, institutional and educational actions to prevent and reduce hazard, exposure, and vulnerability [12]. This requires a comprehensive and holistic disaster-related knowledge at a local level including the landslide risk [13]. Tropical climatic conditions favor that over 90% of the disasters in Costa Rica are hydrometeorological in nature [14]. Landslide studies were extensive in Costa Rica, nevertheless, hazard cartography resolution and its integration with vulnerability, exposure, and risk analysis are limited [15].

The Central American region is characterized by its moderate to high landslide hazard and risk [16,48]. More than 90% of the disasters in Costa Rica are hydrometeorological, 60% are related to floods and 30% to landslides [14]. About 60% of the national territory is mountainous where landslides are common (Fig. 1). In addition, altered lithology, heavy rains, and seismicity makes Costa Rica a suitable territory for landslides [17]. Furthermore, poor agricultural practices, roads with inadequate slope designs, poor water management, and slope cuts without protection make the country highly vulnerable to landslide events [18].

Costa Rica has a continental extension of 51,100 km^2, divided political and administratively in 82 cantons (municipalities). Land use planning and disaster risk assessment are made at municipal scale by law in the country. Therefore, a municipal approach understanding landslide risk can give important tools to local governments, as well as to regional and national decision makers. Despite of the high number of publications, annual reports and impacts of landslides in Costa Rica, a

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national landslide risk index at municipal scale has not been done. Here, this study present a landslide risk index and analyze the landslide risk results at municipal scale for Costa Rica in order to generate a baseline and a method to assess landslide disaster risk at regional or national scales.

2. Morphotectonic and climatic setting: A dynamic country

The Cocos-Caribbean plates subduction margin, the Panama microplate, and the Cocos volcanic range subduction favor Costa Rican tectonic activity [20]. This dynamic has formed three morphotectonic units: forearc, volcanic front, and backarc (Fig. 2; [21]. The fore arc extends along the Pacific coast with an abrupt topography of Cretaceous-Quaternary age [22]. The volcanic front includes the Guanacaste, Tilarán, Aguacate, Central, and Talamanca mountain ranges composed mainly of volcanic and sedimentary rocks of Paleogene-Quaternary age [23]. The back arc extends from the Caribbean plains of the Tortuguero lowlands in north-eastern Costa Rica to the rugged emergent morphology of the southern Caribbean [24]. The climate and precipitation patterns are influenced by the latitudinal migration of the Intertropical Convergence Zone, ENSO, northeast trade winds, cold fronts, and tropical cyclones [25]. The interaction of trade winds and topography produces Pacific and Caribbean climates. The Pacific side presents a bimodal rainfall distribution, while it is difficult to define a dry season for the Caribbean side (Fig. 3).

The high number of endemic species, levels of forest composition and configuration, and a varied biodiversity position Costa Rica as a mega-diverse country, which holds approximately 6% of the worldwide biodiversity, compose of mountain cloud forests, evergreen moist forests, seasonal forests, dry forests, paramos, coastal, and wetlands ecosystems [26]. Deforestation and landscape fragmentation dominated from the 1950s until the mid-1980s. Afterwards, a series of environmental policies reversed deforestation together with the rise of ecotourism and the development of more sustainable production alternatives reaching a forest cover of 51% of the country [27]. In 2018, Costa Rica's population reached five million inhabitants and, during the last three decades, its population shifted from a marked rurality to a clear urban trend reaching 75% of the population in 2011. Currently, the GAM (Greater Metropolitan Area) accounts for 65% of the population (approximately 3 million inhabitants) of Costa Rica occupying 14% of its surface [28]. All these natural and social variables condition the incidence and recurrence of landslides in the country. Most of the landslides in Costa Rica are translational and rotational slides, but debris flows,

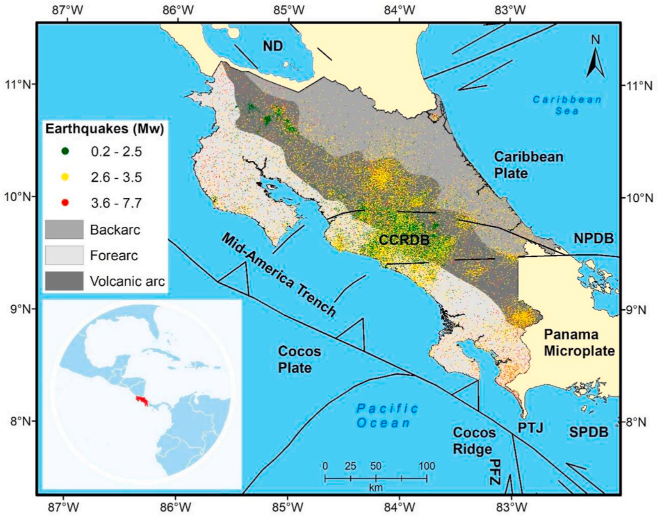

Fig. 2. Location, tectonic framework, and morphotectonic units of Costa Rica. ND: Nicaragua Depression; CCRDB: Central Costa Rica Deformed Belt; NPDB: North Panama Depression Belt; SPDB: South Panama Depression Belt; PFZ: Panama Fracture Zone; PTJ: Point Triple Junction (for details, see Ref. [31]. Instrumental location of earthquakes from 1975 to 2017 [35].

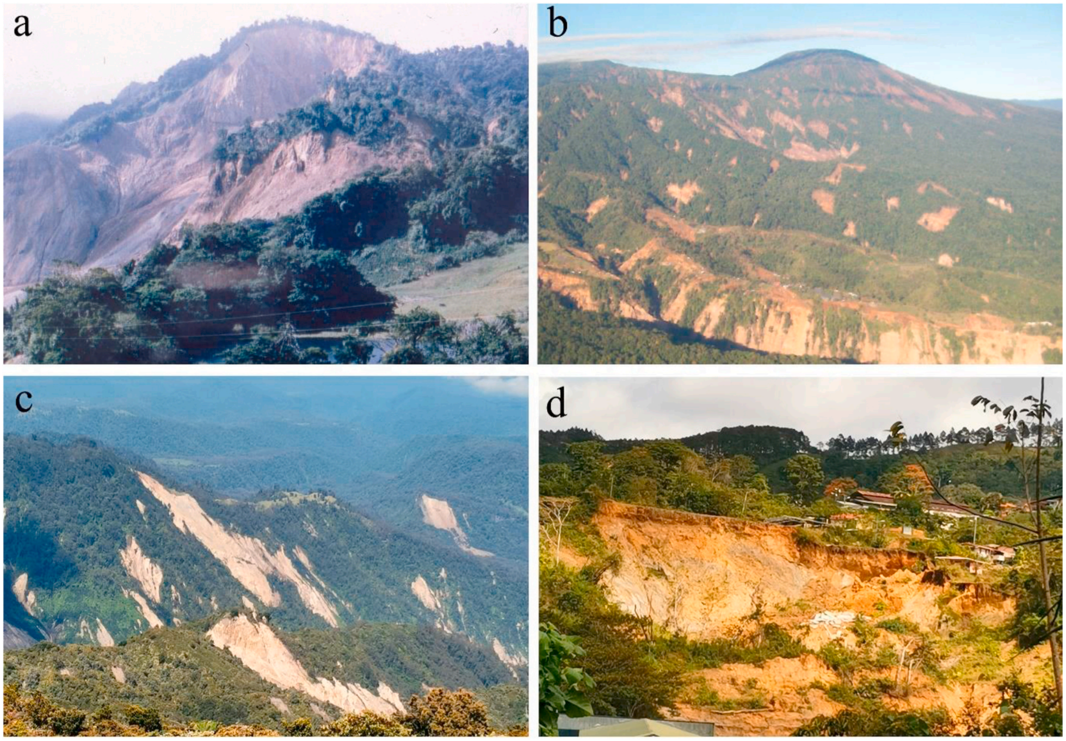

Fig. 1. Past and recent mass movements in Costa Rica. a) Arancibia (Puntarenas) debris avalanche in 2000 (photo by G. Alvarado), b) mass movements after the 2009 Cinchona earthquake (photo by G. Alvarado), c) landslides at the Irazú volcano in 2020 (photo by the author), d) landslide activated in 2018 in San Vito (photo by the author).

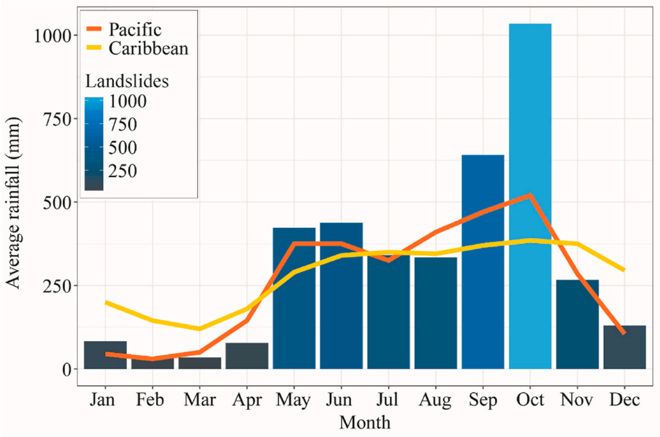

Fig. 3. Costa Rican Pacific and Caribbean rainfall trends (Based on [52], and landslides number by month from 1970 to 2018 [14].

falls, complex slides and even avalanches have been reported in the past [18,29].

3. Materials and methods

3.1. Landslide hazard

Historical knowledge about the landslide dynamics and occurrence in Costa Rica were analyzed through multiple research papers and technical reports. The DesInventar disaster database was used to develop a national landslides catalog in Costa Rica (http://www.desinventar.org). This database provides the greatest spatial detail at municipal and even district level between 1970 and 2018. Costa Rica is one of the few countries where this database has been recorded uninterruptedly. Its information is provided by the National Commission for Risk Prevention and Emergency Attention (CNE), as well as newspaper reports, and the 9-1-1 system. EM-DAT and NatCatSERVICE disaster databases were also revised but no relevant inputs were found due to their event selection criteria. Disaster database results of the main human and material damages by landslides in Costa Rica show that occurred 3835 events where 221 people died, 20 missing, 34 wounded, at least 20,240 were victims, 115,498 affected, 5625 evacuees, 566 relocated, 447 houses destroyed, 4129 houses affected, and the reported loss values in US$ dollars were of 42 million between 1970 and 2018 [14].

To construct a landslide risk index at municipal scale for Costa Rica it was necessary to use all the available national variables in the best possible resolution and extract their information by municipality. Landslide hazard is the division of land into homogeneous areas or domain and their ranking according to the degrees of actual or potential landslide susceptibility, hazard or risk or applicability of certain landslide related regulations [30,32]. A landslide hazard index (LHi) was performed to analyze the number of reports (REP) by municipality (Fig. 4; [14]. First, the mean municipal altitude, mean municipal slope, mean municipal Terrain Ruggedness Index (TRI; [33,34], intensity-duration-frequency curves (IDF curves), instrumental location of earthquakes (EQ) between 1975 and 2017 [35], peak ground acceleration (PGA; [36], lithology susceptibility factor (LIT; see details in Ref. [37], soil profundity, soil texture (SAND, SILT, and CLAY), particle density (PDENS), and bulk density was determined (BDENS; CIA, 2019). Mean municipal altitude (ALT) and SLOPE were calculated from a national DEM (10-m digital elevation model). Meanwhile, TRI was performed in SAGA [38]. Besides, soil profundity, soil texture (sand, silt, and clay), particle density, and bulk density were added (CIA 2019). Furthermore, IDF return periods curves of five (TR5) and 100 years (TR100) extreme precipitation events were used [39,40]; Table 1). The

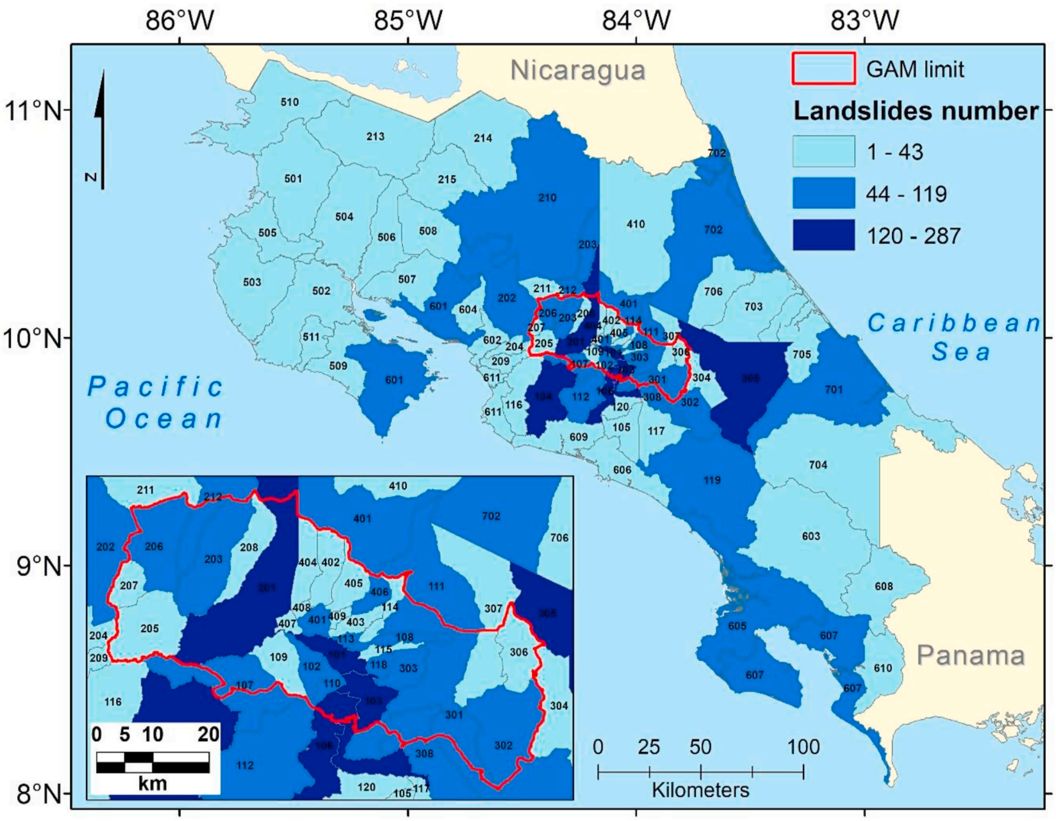

Fig. 4. Municipalities of Costa Rica and their number of landslides between 1970 and 2018. Code list is available in S1. GAM (Greater Metropolitan Area, in Spanish) limit represent approximately the 65% of the national population.

Table 1
National and municipal-scale data layers used in the generation of national-scale landslide hazard, vulnerability and risk indexes and maps. Detailed information of each municipality and variables in S1.

Classification	Data layers	Abbreviation	Source	Scale
Historical mass movements	Landslides reports (1970–2018)	REP	DesInventar	Municipal
Hazard variables	Lithology susceptibility factor	LIT	Based on Mora and Vahrson [37] using Denyer and Alvarado [22]	National: 1:400.000
	Altitude (DEM)	ALT	Geographical National Institute (2005)	1:25.000
	Slope steepness	SLOPE	Geographical National Institute (2005)	1:25.000
	Terrain Ruggedness Index	TRI	Based on Riley [33]	1:25.000
	Intensity-duration-frequency precipitation curves (5-year; 100-year)	TR5; TR100	Rojas-Morales, [39]; Vargas-Valverde, [40].	National
	Earthquakes distribution	EQ	RSN [35]	Municipal
	Peak ground acceleration	PGA	Climent et al. [36]	0.1°
	Soil textures	SAND; SILT; CLAY	CIA (2019)	National
	Soil particle density	PDENS	CIA (2019)	National
	Soil bulk density	BDENS	CIA (2019)	National
Vulnerability variables	Population projection (2020)	POP	INEC [45]	Municipal
	Population density	PD	Calculated (2020)	Municipal
	Social Development Index	IDS	MIVAH (2017)	Municipal
	Municipality areas	AREA	Geographical National Institute (2005)	1:50.000

selected variables had the best resolution available for the entire country at municipal scale. Moreover, a Pearson correlation method [41] was applied to eliminate the variables within high collinearity. A Generalized Linear Model (GLM) was developed to describe linkages between landslides reports at municipal scale (REP) and the rest of variables. Based on Akaike Information Criterion (AIC) (Anderson and Burnham 2004) that predicts error and quality of the estimators for statistical models (as GLM) for a given set of data [17,42], a backward selection was used to contrast the null hypothesis (i.e., REP∼ 1) against the alternative hypothesis (i.e., REP ∼ TR5+EQ).

3.2. Landslide vulnerability

Consistently, another index was developed considering vulnerability characteristics of the municipalities of Costa Rica (LVi). Landslide vulnerability is the degree of loss to a given set of elements at risk resulting from the occurrence of a landslide of a given magnitude in a specific area [43,44]. In this study, it was defined through existing social variables at the municipality scale. The used variables have the best available resolution for the entire country at municipal scale. Area (AREA), population (POP), population density (PD), and social development index (IDS) made by the Ministry of National Planning and Economic Policy of Costa Rica (MIDEPLAN, 2017) were used (Table 1). IDS evaluates educative, public health, civic participation, and security variables of every municipality to show an integrated national panorama. The null hypothesis (i.e. REP∼ 1) was contrasted against the selected alternative hypothesis (i.e. REP ∼ POP + AREA-IDS).

3.3. Landslide risk

Model parameters were then used to evaluate the weight of each covariable explaining the landslide hazard and vulnerability associated with landslide municipal reports for five decades. Both models' covariables were standardized using z-score. The response variable was log-transformed to meet the normality assumption. Finally, tested alternative hypotheses for landslide hazard (LHi = TR5+EQ) and vulnerability (LVi = POP + AREA-IDS) were normalized and multiplied in order to determine municipalities' landslide risk index (LRi = LHi*LVi). All the municipal landslide indexes were classified in three ranges according to Jenks natural breaks method to accurately represent the spatiality of data attributes [45].

4. Results

4.1. Landslide hazard analysis

Landslide hazard by municipality is explained statistically by the selected alternative model (AIC = 238.24), which had better precision than the full hypothesis (AIC = 243.97) and null hypothesis (AIC = 261.47). Therefore, the model suggests that the best generalized linear model supports an interaction between terrain ruggedness, 5 year-IDF curves and earthquakes distribution (REP ∼ TRI + TR5+EQ). Table 2 gives the parameters of the model, indicating that the most significant effect on onset probability of municipal landslide hazard in Costa Rica is given by terrain ruggedness, 5 year-IDF curve and earthquakes distribution. Slope angle had a high collinearity with TRI, and the latter explain statically better the occurrence of landslides by municipality. Otherwise, lithology susceptibility factor, peak ground acceleration nor different soil textures did not have strong statistical correlations with the occurrence of landslides perhaps due to the wide municipal scale.

The interaction between terrain ruggedness index, 5 year-IDF curves and earthquake distribution (REP ∼ TRI + TR5+EQ) was used to determine the landslide hazard index (LHi; Fig. 5). Tropical weathered slopes are prone to slide due to earthquakes and/or rainfall. The earthquakes' impact on slope weakening has a direct relation with the subsequent rainfall triggering of landslides on mountain regions. Ground movements that occur at close distance from the source of the earthquake and continuous and/or extraordinary rainfall events could trigger landslides. The GLM results were classified in three groups: high, medium, and low (S1). The highest values of landslide hazard are in Pérez Zeledón (119), Parrita (609), Turrialba (305), Dota (117), and Quepos (606) municipalities. All of these municipalities have the highest number of earthquakes in the historical record, while Parrita and Quepos also have very high TR5 values. The medium values are associated with municipalities where only one model term is high, i.e. considerable

Table 2
Parameters used to model municipal landslide hazard: Null deviance is 113.888 on 80° degrees of freedom (df), residual deviance is 77.389 on 77° df, and the AIC is 238.24. The significance Pr(>jzj) is the likelihood of discover the observed Z-ratio in the distribution of Z by a critical point of jzj. ***P = 0, **P = 0.01,.P = 0.1.

Model terms	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	2.6636	0.7985	3.336	0.0013**
TRI	0.6245	0.1639	3.81	0.0002***
TR5	−0.0074	0.0098	−0.758	0.4505
EQ	0.0003	0.0002	1.785	0.0781

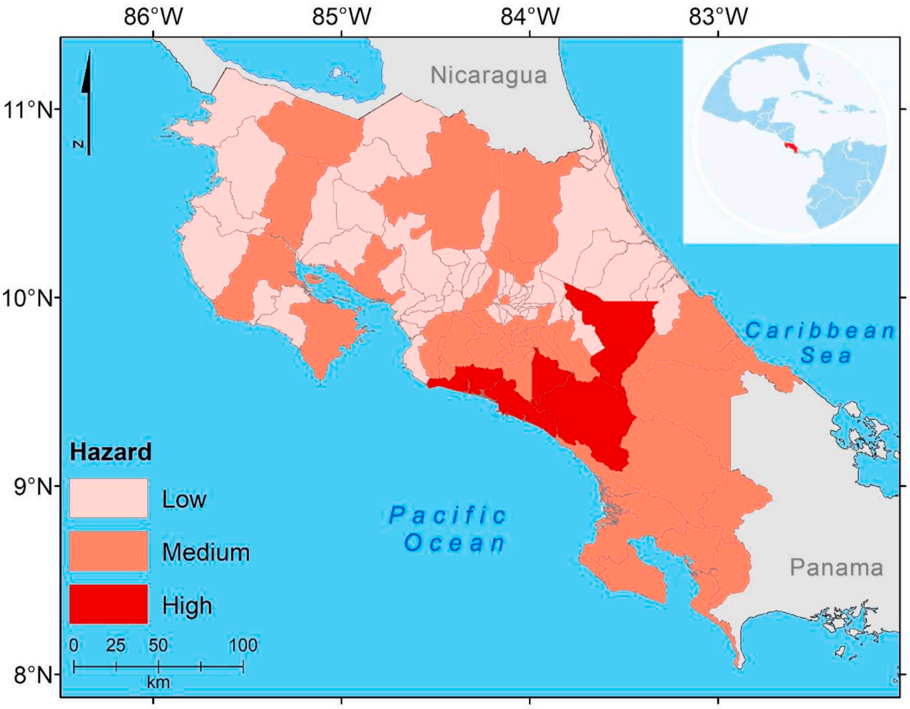

Fig. 5. Landslide hazard index by municipality for Costa Rica.

EQ record but mean or low TR5. This is the case in municipalities even with steep topography such as Tarrazú (105), Coto Brus (608), Puriscal (104), Paraíso (302), Alajuela (201), Puntarenas (601), and Desamparados (103). On the other hand, the combination of municipalities with low landslides records are consistent with a low number of reported earthquakes. In contrast, small-size municipalities reported few landslides despite of having high EQ and TR5 values. Furthermore, municipalities with low TRI values are commonly related with low landslide hazard index values such as Los Chiles (214), Pococí (702), Sarapiquí (410), Liberia (501), or Siquirres (703).

4.2. Landslide vulnerability index

Municipal landslide vulnerability is statistically explained by parameters based on the AIC criterion that supports the alternative model (AIC = 240.19) against the full hypothesis (AIC = 241.23) and null hypothesis (AIC = 261.47). Moreover, the results suggest the best generalized linear model supports an interaction between population, municipality area and Social Development Index (REP ~ POP + AREA-IDS). Table 3 offers the model parameters, showing that the weightiest influence on onset possibility of municipal landslide vulnerability in Costa Rica are given by population, municipality area and Social Development Index, as shown by z-ratio tests of parameter estimates.

The interaction between population, municipality area and Social Development Index (REP ~ POP + AREA-IDS) was used to determine the landslide vulnerability index (LVi). Landslide vulnerability in Costa Rica is related to high population municipalities conditioned by their area and social development. There are large rural and not populated municipalities; contrarily there are very small especially urban and very populated units. The GLM results were obtained for three groups: high, medium, and low (S1). Highest vulnerability values were obtained by San José (101), Alajuela (201), Desamparados (103), San Carlos (210), Cartago (301), Pococí (702), Pérez Zeledón (119), Heredia (401), and Puntarenas (601; Fig. 6). San José (101), Alajuela (201), Desamparados (103), Cartago (301), and Heredia (401) are located in the Great Metropolitan Area (GAM). The GAM is a region which concentrates ~65% of the Costa Rica population in only 14% of its territory. These urban municipalities have populations from 143,000 to 347,000 inhabitants, small to medium size territories, and medium IDS values. San Carlos (210), Pococí (702), Pérez Zeledón (119), and Puntarenas (601) have larger territories, mostly rural, populations between 140,000 and 200,000 inhabitants, and a medium-low IDS. Approximately 3 out of 5 municipalities with medium values (59%) have populations below the national municipal average (63,101 inhabitants). More than the half (64%) of these municipalities have areas lower than the national municipal mean (630 km^2). Slightly over half of municipalities (56%) with medium values are located outside the GAM and are mainly rural territories. On the other hand, low value municipalities have populations below 39,000 inhabitants and 75% of these municipalities have areas lower than the national municipal average.

Table 3
Parameters used to model municipal landslide vulnerability: Null deviance is 113.888 on 80° df, residual deviance is 81.331 on 77° df, and the AIC is 240.19. Pr(>jzj) is the probable finding of the observed Z-ratio by a critical point of jzj in the normal distribution of Z. ***P = 0, **P = 0.01, *P = 0.05,.P = 0.1.

Model terms	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	3.45E+00	4.85E-01	7.118	4.97E-10***
POP	1.10E-05	1.99E-06	5.538	4.09E-07***
AREA	−3.65E-04	2.27E-04	−1.605	0.113
IDS	−1.09E-02	6.98E-03	−1.565	0.122

4.3. Landslide risk index

The multiplication between hazard and vulnerability indexes were used to determine the landslide risk index (LRi). The results were classified in three groups: high, medium, and low (S1). Highest risk values were obtained for Pérez Zeledón (119), Alajuela (201), Desamparados (103), San Carlos (210), Cartago (301), and Turrialba (305; Fig. 7). These municipalities have values of 5 year-IDF precipitation curves significantly over the country average. Average number of earthquakes by municipality were 1300, which is considerably higher than the national mean (495), except for San José (101). IDS of these municipalities (58) is similar to national average (55). The average population of these

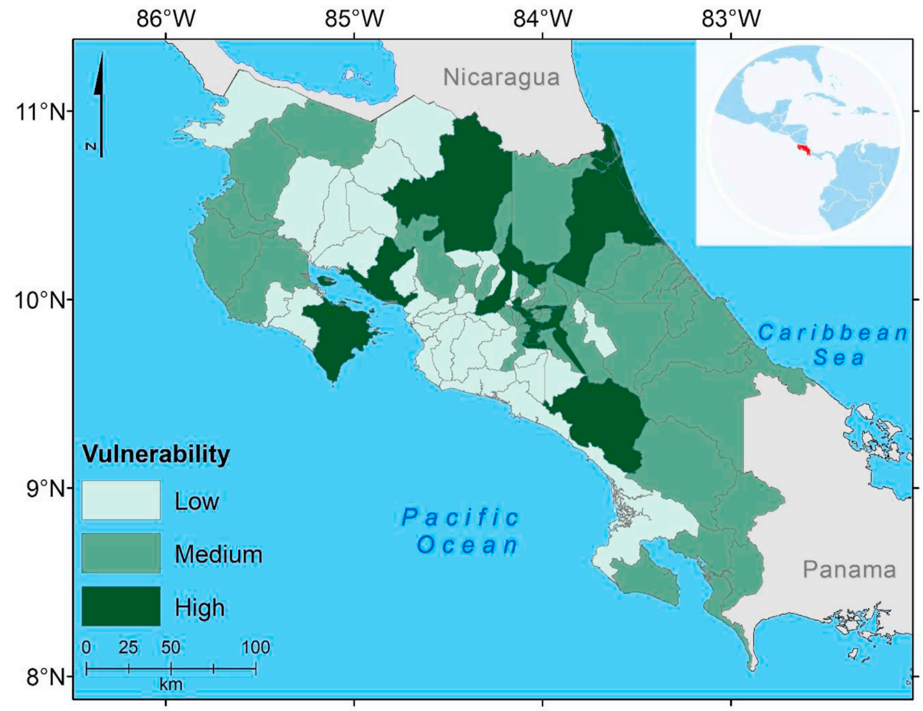

Fig. 6. Landslide vulnerability index by municipality for Costa Rica.

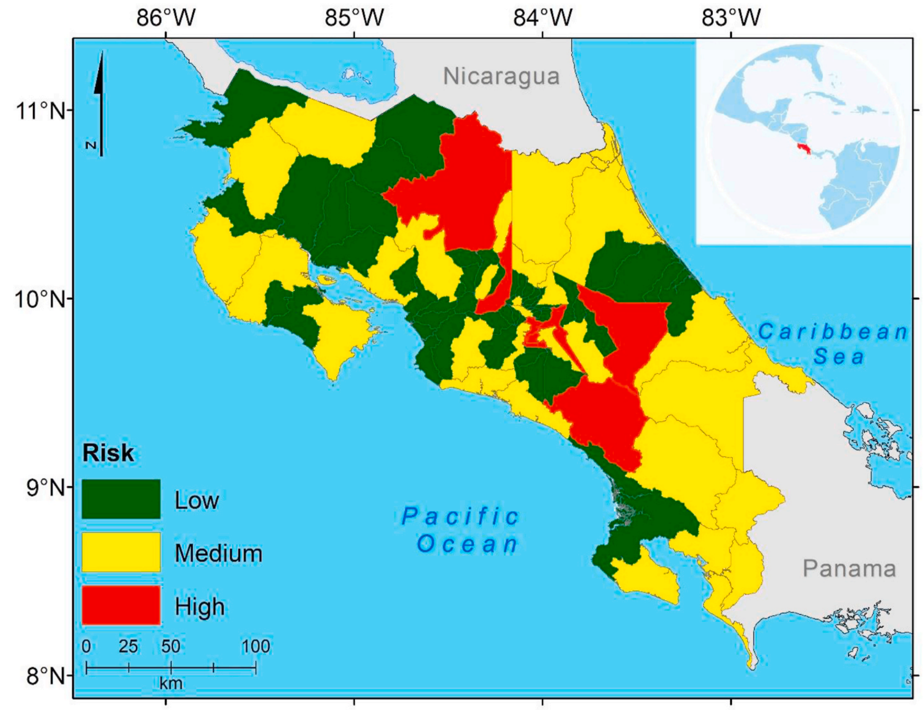

Fig. 7. Landslide risk index by municipality for Costa Rica.

seven municipalities is 212,000 inhabitants, a very significant number considering the national mean (63,000). The municipalities of Alajuela (201), Desamparados (103), and Cartago (301) are in the GAM which are mainly urban with areas below the national mean (630 km^2). On the other hand, Pérez Zeledón (119), San Carlos (210), and Turrialba (305) are rural municipalities with extensions over 1587 km^2. Despite some of these municipalities have significant extensions, their mean population density is 1627 in/km^2, much higher than national average of 855 in/km^2. Medium risk municipalities have similar average national values of 5 year-IDF precipitation curves (68) and population (72,000). The number of earthquakes (841), and municipality's areas (1051 km^2) are over the national mean. The IDS (42) and the population density (385) are below national average. Low risk municipalities have similar values of TR5 (68) and IDS (61) to the national mean. Municipalities area (362 km^2), population (37,000), and number of reported earthquakes (217) are lower than the country average. Meanwhile, population density is higher in these municipalities (973) than the national mean.

5. Discussion

This study used the landslide occurrence in Costa Rica at municipal scale to perform two generalized linear models using ten hazard and four vulnerability variables. The model results led to landslide hazard, vulnerability and risk indexes for every municipality of the country in order to assess national landslide disaster risk.

5.1. Landslides controlling factors

The results suggest that TRI, EQ and TR5 were the best generalized linear model supported terms to explain the historical landslide hazard distribution. The earthquakes' influence on slope weakening has a direct relation with the subsequent rainfall triggering of landslides in mountain landscapes. Landslides have been widely related to rainfall intensity-duration relations [46] or to seismic activity [47]. Central America's and Costa Rica's high seismicity due to its tectonic complexity makes this region particularly susceptible to slope weakening [20]. The region has a substantial history of earthquake-induced landslides [19]. Particularly for Costa Rica, its seismicity is abundant in the Pacific coast, especially between the coastline and the Mesoamerican Trench, associated with the interaction between Cocos, Caribbean, and Panama plates [49]. Other major tectonic features include the Panama Fracture Zone (PFZ), the North Panama deformed belt (NPDB), and the Central Costa Rica deformed belt (CCRDB) [50]. These crustal deformation broad zones are proposed as the boundaries between the Caribbean plate and the Panama microplate [51]. Interestingly, the highest hazard value municipalities of this study coincide along these zones (Pérez Zeledón-119, Parrita-609, Turrialba-305, Dota-117, and Quepos-606).

El Niño-Southern Oscillation temporal and spatial variability heavily influences rainfall oscillations [52]. Complex responses (warm or wet) vary in terms of their signs, magnitudes, duration and seasonality between water basins draining towards the Pacific and the Caribbean [53]. These two slopes behave differently and likely respond in opposite ways to ENSO conditions [25]. On the Pacific side of Costa Rica, El Niño events generally lead to drier conditions, whereas La Niña events favor wetter conditions [54]. This condition is slightly the opposite in the Caribbean side of Costa Rica. Moreover, a statistically significant positive linear trend has been observed in the annual number of intense hurricanes in the Caribbean Sea since the 1970s [55]. These characteristics facilitate the occurrence of extreme hydrometeorological phenomena related to the ENSO, or more specifically, during the passage of cold fronts and tropical cyclones. Accordingly, the region also has a very high correlation between mean daily rainfall totals and mean daily landslides [56]. The occurrence of such extremes has been demonstrated to trigger landslides in Central America [57]; Pérez-Briceño et al., 2016) and Costa Rica [58]. The municipalities having high and medium hazard values in this study coincide with previous studies in the country [59–61]. Most of these municipalities are located in the Pacific basin where tropical cyclones impact strongly during their effects over the country. Seismic preconditioning and subsequent extraordinary rainfall conditions generating landslides have occurred several times in Costa Rica [17]. This cascading effect is reported throughout Costa Rica due to tectonics and intense rainfall coupling.

5.2. Vulnerability conditions for landslides

The highest vulnerability values were obtained for San José (101), Alajuela (201), Desamparados (103), San Carlos (210), Cartago (301), Pococí (702), Pérez Zeledón (119), Heredia (401), and Puntarenas (601). These results are associated with populated mostly urban or large-sized rural municipalities with low social development (MIDEPLAN, 2017). Many municipalities that already have a continued urban growth in mountainous landscapes such as Alajuela (201), Desamparados (103), Pérez Zeledón (119) and Heredia (401) will be more affected by landslides [62]. Another problem for urban areas is the increase of impervious surfaces coupled with an inefficient pluvial sewer system as identified in the past in San José (101), Alajuela (201), Cartago (301), Heredia (401) or Desamparados (103; [63]. Moreover, poor inter-institutional coordination for the prevention of emergencies mainly in the rainy season favor landslide occurrence [64]. Rural municipalities, as many of the identified as Pérez Zeledón (119), San Carlos (210) or Puntarenas (601), have clear lags in quality education, job options, and specialized health services due to the country's centralization in the GAM (MIDEPLAN, 2017). These limitations push young people to migrate to the GAM or abroad looking for better opportunities. Therefore, the workforce is reduced in the rural municipalities generating a limited economic development and increased vulnerability facing disasters such as landslides.

Every year, Costa Rica uses ~86 million USD (~1% of the national gross domestic product, GDP) repairing and rehabilitating the effects of natural disasters [65]. Recent disaster impacts due to the tropical cyclones are clear examples of the increasing national vulnerability. The cost of recovery from Hurricane Otto (2016) represented 0.394% of the national GDP, while tropical storm Nate (2017) summed 1.283% of the GDP. These disaster consequences were predominantly in road infrastructure (bridges and roads) where Costa Rica has a clear development delay [66]. The impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption [67]. Furthermore, a strong association between informal settlements with high hazard exposure are common in developing countries [68]. The increasing vulnerability conditions in Costa Rica due to the inefficient territorial management lead to the occurrence of cascading disasters [17].

5.3. Spatial distribution of landslide risk in Costa Rica

Historical national landslide catalogues for Costa Rica have been done by Mora et al. [69]; Peraldo and Rojas [70]; Arroyo et al. [71]; and Vallejos et al. [18]. The historical occurrence of landslides has been reported along volcanic slopes of the Central and Guanacaste Volcanic Cordilleras [72–74]. Specific landslide studies in volcanoes have been made in Poás [75–77], Irazú [78–81], Barva [15] and Miravalles [17]. Moreover, specific seismic events such as Limón in 1991 [82]; Mora and Mora, 1994; [83], Cinchona in 2009 [84–89], and Sámara in 2012 [90] have presented numerous publications.

Landslide processes in certain municipalities have been taking more attention of scientists and decision makers during the last four decades. Some of these areas are located in municipalities determined with a high hazard, vulnerability or risk to landslides. For example, Puriscal (104), a mainly rural municipality south of San José province, has been widely studied. A local seismic swarm and an earthquake in 1990, in addition to an altered land caused by intensive agriculture, have provoked continuous instability [91–94]. An eventual debris flow or lahar such as the occurred in 1963 in Cartago (301) has been analyzed in the past [95–97]. The historical impact of land use change and train lines activity in Turrialba (305) have been extensively analyzed [98–102]. Other dynamic cases have been studied in Pérez Zeledón (119) associated with the impact of Buenavista earthquake in 1983 as well as the successive tropical cyclones which triggered several landslides [103–109]. During the last decade, special attention has been given to develop the studies of landslides south of the GAM municipalities such as Cartago (301), Acosta (112), El Guarco (308), Aserrí (106), Desamparados (103), Alajuelita (110), Mora (107), Escazú (102), and Santa Ana (109). These municipalities present a rapid urban growth over altered volcanic or sedimentary rocks [62,64,110–112,123]. Other studied cases have been located in urban and periurban municipalities of the GAM such as Poás (208; [113], Alajuela (201; [122]), and Moravia (114; [114].

5.4. Risk implications and potential solutions

The highest risk values were obtained for Pérez Zeledón (119), Alajuela (201), Desamparados (103), San Carlos (210), Cartago (301), and Turrialba (305). Earthquakes and intense rainfall on steep slopes were key variables to explain landslide hazard in some municipalities. Meanwhile, municipal area, population, and social development were the more representative variables to analyze landslides vulnerability. For instance, combined seismic and hydrometeorological occurrence can lead to compound events and amplify/intensify disasters [115]. It is compulsory to monitor regions that have previously been affected by earthquakes, especially during extraordinary rainfall events such as tropical cyclones [116]. Baseline information for disasters in Costa Rica should be enhanced and the cartography of natural hazards must be improved [117]. The use of low cost technologies as drones can improve the way baseline data is obtained and produce high resolution landslide maps [97]. However, the number of investigations on vulnerability and risk in the country should increase in order to reduce disasters [106]. The international landslide classification must be implemented at national, regional and local scales in order to communicate the same dynamics [29]. Additionally, it is important to untie national level dependence in disaster risk management decision-making on the CNE [118]. Furthermore, the implementation of early warning systems with a water basin perspective and effective risk communication tools are critical in order to reduce casualties and economical losses not only in Costa Rica but also in very dynamic tropical and developing countries [119]. Moreover, land use planning measures in parallel with engineering projects are very useful to prevent disasters at long term at municipal scale [120]. Decentralization of government and disaster management could improve disaster governance in municipalities of Costa Rica. This process could close the distance between citizens and their government, improving regional and local governance capacity [121]. The success on risk assessment, planning and the implementation of mitigation measures in Costa Rica depend on the inter-scale coordination [56].

6. Conclusions

Earthquakes' impacts on slope weakening have a direct relation with the subsequent rainfall triggering of landslide hazard on mountain regions in Costa Rica. Consequently, landslide vulnerability is associated with very populated municipalities conditioned by their spatial extension and social development. The highest risk values were obtained for Pérez Zeledón (119), Alajuela (201), Desamparados (103), San Carlos (210), Cartago (301), and Turrialba (305) which are mostly urban and very populated or large size rural with low social development municipalities. Landslide assessments at a national scale are scarce despite their importance for territorial and disaster risk management stakeholders. The design of this national landslide risk assessment methodology first considers the user's needs according to its impact in political and administrative decision-making. The main user in Costa Rica is the CNE, who uses this information at municipal levels to define areas for further detailed studies. The municipalities are additional elements identified as relevant for the landslide risk assessment model design. In Costa Rica, municipalities are responsible by law for their territorial planning and local emergency committees. Local authorities can now be warned about the landslide risk that their areas are facing and coordinate with the CNE to allocate resources for a local landslide mitigation program. This study encourages to follow up with studies at a larger scale and develop a national landslide risk program. These goals agree with improving landslide mapping, natural hazards education, early warning systems, and capacity building. In tropical and developing countries facing landslide occurrence on a regular basis, this methodology can be used on local government scales to achieve national or regional analyses.

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Declaration of competing interest

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Appendix A. Supplementary data

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