Evaluation of The Landslide Processes In Cayambe, Pichincha, Ecuador

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Research Article

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RESEARCH

Evaluation of the landslide processes in Cayambe, Pichincha, Ecuador

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Abstract

The present work proposes the use of the statistical method of frequency ratio (RF) and the hierarchical analytical process (AHP) to obtain zoning maps of the landslide processes, determining the susceptible areas in the territory of the Cayambe canton located in the province of Pichincha in Ecuador. Statistical methods use sample data based on the relationship between landslides and causal factors, evaluating the combination of these data objectively. As results, it was identified that the analysis of the landslide indices according to the FR method and the AHP method, shows that the inclination of the slope and the exposure are the important factors in the analysis of the susceptibility of the territory. However, a separate analysis shows that, for the FR method, the stratigraphic genetic complex factor is the most relevant, while for the AHP method, the most important factor is the steepness of the slope. On the other hand, the analysis of the distribution of landslides by parish shows that rural parishes present a greater number of landslide processes. In this way, it is highlighted that the Cangahua rural parish has 42% of the total landslides identified in the canton. Followed by the parishes Santa Rosa de Cusubamba and San José de Ayora, together with 29% of the landslides. For the rest of the parishes, the landslide rate does not exceed 9%.

Keywords: Slope processes; frequency ratio method; landslide hazard; engineering and geological conditions

Introduction

Geo-hazards represent severe and extreme weather and climate events that occur naturally worldwide, with multidimensional and multidisciplinary character. Most geo-hazards are frequently related to mountainous regions, in this sense, it has been shown that the Andean Mountains often suffer shallow landslides, debris flows, and rock slope failures due to its high variability in precipitations related to their orography, altitude, and microclimates. Landslide risk studies focusing on South America have found that precipitation, population density, and land use are significant factors to study. In the Andes a few landslides risk works have used diverse modeling and mapping approaches, in such countries as Colombia (Envigado city) and Ecuador (Quito, Loja cities) [Puente et al(2021)Puente, Egas, and Teller, Temesgen et al(2001)Temesgen, Mohammed, and Korme, Getachew and Meten(2021), Nicu(2017), Gariano and Guzzetti(2016)].

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In addition to the above, in statistical terms, it is well known that over 95% of all disasters and fatalities related to landslides, in general, occur in developing countries, as a direct consequence of the characteristics of the territory, a growing urban population, uncontrolled urbanization, environmental degradation, and densification. Nowadays it is indisputable that climate changes affect the stability of natural and engineered slopes and also have consequences on landslides, especially precipitation changes in some regions [Puente et al(2021)Puente, Egas, and Teller, Temesgen et al(2001)Temesgen, Mohammed, and Korme, Getachew and Meten(2021), Nicu(2017), Gariano and Guzzetti(2016)].

La evaluación de la estabilidad de las laderas y del peligro de deslizamientos es una de las tareas más importantes de los estudios de ingeniería y geológicos para casi todos los tipos de construcción. Seguramente, ningún sector de la ingeniería depende más de la estabilidad de las laderas y los taludes de excavaciones artificiales como la construcción de carreteras y ferrocarriles [Симонян, B.B.(2011)]. Es así que, una definición deficiente de las zonas peligrosas puede generar graves peligros durante y después la construcción [Симонян, B.B.(2011), Edigbue et al(2021)Edigbue, Al-Mashhor, Plougarlis, Soupios, Tranos, Kaka, Al-Shuhail, and Al-Garni]. Over time, academic and professional communities have begun to pay close attention to landslide susceptibility. Nowadays, the challenge lies in producing more detailed knowledge. The number of landslide investigations concerning methods and the progress in susceptibility has grown rapidly. Several approaches have been developed for landslide zonation within this framework [Paudel et al(2016)Paudel, Oguchi, and Hayakawa, Temesgen et al(2001)Temesgen, Mohammed, and Korme, Getachew and Meten(2021)].

The approaches developed for landslide zonation can be grouped into qualitative and quantitative methods. Many pioneer's works in this field concern qualitative studies. Qualitative methods are based on expert opinions or entirely on the judgment of the person that conducts the landslide susceptibility or hazard assessment. It includes field geomorphological analysis and overlaying of index maps with or without a weighting approach. The subjectivity of these methods was addressed by the adoption of quantitative assessment methods [Paudel et al(2016)Paudel, Oguchi, and Hayakawa, Tan et al(2021)Tan, Bai, Zhou, Hu, and Qin, Nicu(2017)]. Quantitative methods are data-driven and based on mathematical expressions between landslide controlling factors and landslide events. These methods can be either statistical or deterministic. Statistical approaches have become increasingly sophisticated in the research domain. These approaches are based on numerical values driven by the relation between landslide distribution and the factors.The disadvantages of statistical approaches include poor data quality and inadequate understanding of the elements [Paudel et al(2016)Paudel, Oguchi, and Hayakawa, Tan et al(2021)Tan, Bai, Zhou, Hu, and Qin, Nicu(2017), Daniel et al(2021)Daniel, Ng, Abdul Kadir, and Pereira].

Deterministic approaches are best suited for territories with similar landslide types, geological settings, and geomorphological conditions. These approaches can be applied in small to medium-sized areas, having limited use for susceptibility modeling over larger areas [Getachew and Meten(2021), Van Westen and Terlien(1996), Daniel et al(2021)Daniel, Ng, Abdul Kadir, and Pereira, Jelínek and Wagner(2007)]. The use of geographic information systems (GIS) and environmental modeling along with statistical approaches has made landslide zonation more efficient and inexpensive [Nicu(2017), Daniel et al(2021)Daniel, Ng, Abdul Kadir, and Pereira]. Landslide zonation takes two predominant forms: event mapping (landslide inventory map) and event controlling parameter assessment which is often used in conjunction with each other.

Study area

Ecuador has high tectonic and seismic activity due to its location in the Pacific Ring of Fire. The climatic conditions of the territory are configured by the presence of the Intertropical Convergence Zone (ITCZ), which is a low pressure belt that surrounds the planet and generates a large amount of rainfall that provides warm and humid air. These characteristics mean that the country is regularly exposed to catastrophic events of hydrometeorological, geological and mixed origin that cause serious damage to the infrastructure of cities, generating human losses and negative impacts on the national economy. That is why the effective management of geological disasters has become one of the main challenges facing the country [Ortega(2012), Sanchez and Castro(2008)].

Landslides are the natural phenomena that most frequently affect the mountainous region of Ecuador. The Desinventar-Sendai database (`www.desinventar.org`) shows that during the period 1970-2006, landslides were the phenomena that generated the most deaths in the country. Reports of negative impacts show a certain upward trend since the 1990s [Ortega(2012)].At present, landslides occupy the second place in the phenomena with the highest mortality rate. Of the total landslides identified up to 2018, it is estimated that 64% were caused by heavy rains typical of the winter season; and that the roads are the most affected infrastructure. The socioeconomic problems caused by landslides in the country are mainly related to the disorganized growth of cities, the lack of comprehensive engineering studies, and the limited exploration of the territory, prior to construction.

This research evaluates the susceptibility of the territory of the Cayambe canton to landslides. For this, the information referring to the geology of the territory is collected, systematized and analyzed, coming from the geological funds available at the national level. Taking into account the analysis of the information from the selected sources, it is proposed to define the limits of landslides and their risks for human activity, for which susceptibility maps of landslide processes are prepared, using the statistical method of the ratio of frequency (FR) and hierarchical analytical process (AHP).

Materials and methods

Within the analysis of susceptibility to landslide processes, it is necessary to consider the characteristics of the terrain and its location, through the study of climatic, geological, hydrological, hydrogeological factors, among others.

External factor

Volcanism.- The snow-capped Cayambe volcano is an inactive volcano, but it is considered that it may enter into activity in the long or medium term, the eruption probability is not high, however, periods of activity have been recorded in December 2002 and March 2003. The last recorded eruption dates from around the 18th century. It is estimated that it has an eruptive period of approximately 500 years [Moreno et al(2015)Moreno, Luis, Garzón, Gavilanes, Carrera, and Bernal, Campo(2003)].

Seismicity.- The canton of Cayambe is not only subject to high-impact seismic movements caused by tectonic plates that destabilize local geological faults, but it is also subject to earthquakes caused by volcanic activity [Moreno et al(2015)Moreno, Luis, Garzón, Gavilanes, Carrera, and Bernal, Norma Ecuatoriana de la Construcción(2014)]. The last major earthquake that affected the country occurred on April 16, 2016 at 6:58 p.m., off the coast of Ecuador with a magnitude of 7.8. The earthquake affected 23 provinces of the country, as well as places in neighboring countries [Dávila et al(2018)Dávila, Cuesta, Villagómez, Fierro, León, Guerrero, and Vallejo].

*Geographic and climatic characteristics.-*The study territory, the Cayambe canton, is located in the Sierra geographic region, in the inter-Andean region.

The canton of Cayambe is located north of the Ecuadorian Andes, at 2830 meters above sea level, northwest of the province of Pichincha, at the foot of the Nevado Cayambe volcano. The city of Quito, the capital of Ecuador, is located 80 Km away (see figure 1).

The study territory has an area of approximately 1195 Km^2, which represents 14% of the total area of the province of Pichincha.

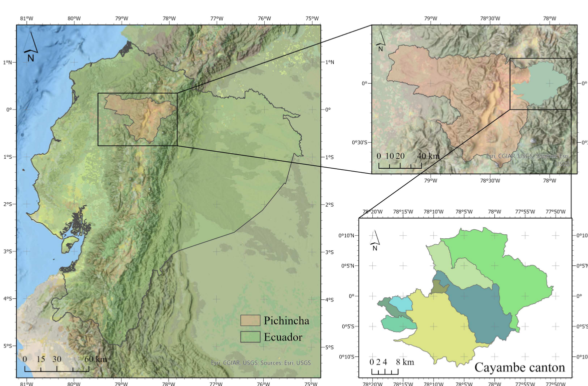

Figure 1: Study area location

The canton of Cayambe consists of eight parishes, of which two are urban (Cayambe, Juan Montalvo) and six are rural (Ascázubi, Cangahua, Olmedo, Oton, San José de Ayora and Santa Rosa de Cusubamba) (see figure 2).

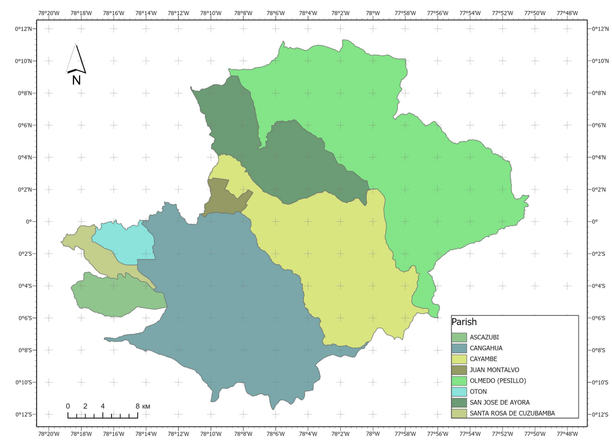

Figure 2: Administrative units of the canton of Cayambe

The Cayambe canton has a semi-humid and humid equatorial mesothermic climate. This climate is characteristic of the Andean mountains without taking into account the protected valleys and areas above 3000-3200 meters above sea level. The equatorial mesothermic climate varies between semi-humid to humid and is characterized by a temperature that is around 12-20°C; the annual precipitations are distributed in two rainy seasons, that oscillate between 500-2000 mm; extreme maximum temperatures do not exceed 30°C, and minimum temperatures rarely fall below 0°C; relative humidity ranges from 65% to 85%, and the duration of insolation ranges from 1000 to 2000 hours per year [Pourrut(1983)].

The climate of a territory is determined by analyzing the following factors: rainfall, average temperature, average maximum and minimum temperature, maximum and minimum absolute temperature, cloud cover, wind speed and relative humidity analyzed as over 25 years, through obtaining data from different meteorological stations, according to their position in flat coordinates and their height in the territory (see table 1).

The study of climatic factors showed that the average annual temperature in the Cayambe canton is 11.9 °C; while the average monthly temperature ranges between 11.2 °C and 12.3 °C. The warmest month is May and the coldest is September. The average relative humidity of the canton is 80% and the average elasticity of water vapor is 10.93 GPa. Annual precipitation at the M023 weather station is 826.1 mm, with monthly variations of 22-83 mm. At station M344 an annual rainfall of 591.2 mm was recorded, with monthly variations of 5.6-67.2 mm. Station M359 reports an annual rainfall of 1016.2 mm; with a monthly maximum of 125.3 mm, and a minimum of 26.6 mm. It was identified that the precipitation is irregular during the year.

Table 1: Weather stations in the canton of Cayambe

Code	Meteorological station	Coordinates		Altitude	Observation
		East	North		
M023	Olmedo-Pichincha	825692	1001569	3120	Conventional weather station
M344	Cangahua	815332	9993576	3140	Rainfall monitoring station
M359	Cayambe	818117	1000560	2840	Rainfall monitoring station

Wind speed during the year varies little, with a maximum annual speed of 4.3 m/s and a minimum of 2.8 m/s.

Geological structure and relief
Rock and relief are among the least modified features of the landscape. The relief has a direct impact on the microclimatic characteristics of the territory, the formation and development of runoff, the nature of the land cover, vegetation and wildlife. Likewise, it largely determines the use of natural resources and the settlement system of the territory. On the other hand, it influences the propagation of dangerous and unfavorable geomorphological processes, such as linear erosion, gravitation, landslides and other processes [Позаченюк Е. А. Петлюкова Е. А.(2016)].

The Cayambe canton is located in the Andean Cordillera, which defines its diverse orography. The formation of the Andes began at the end of the secondary epoch, at the end of the Late Cretaceous, with the subduction of the Nazca Plate under the South American plate; Later volcanic events such as Angochagua, Cayambe and Cusin covered the territory with blocks and powerful layers of volcanic products, which generated volcanic relief and lava flows in the eastern and northern parts of the canton. The final stage of Quaternary volcanic activity is represented by the Cangahua Formation (volcanic deposits). Finally, the action of the glaciations redefined the pre-existing landforms, forming glacial cirques, U-shaped valleys and moraines.

The final process of the origin of the landforms is known as fluvial action, this is the cause of the appearance of fluvial geoforms, such as terraces at different levels and the continuous erosion of landforms. The most representative geological formations of the Cayambe canton are volcanic, followed by glacial, colluvial and alluvial deposits. The geology of the Cayambe canton is characterized by nine geological formations, as presented in a previous study by describing the geological formations [Moreno et al(2015)Moreno, Luis, Garzón, Gavilanes, Carrera, and Bernal].

Hydrological and hydrogeological conditions
The drainage zone of the study area corresponds to the Esmeraldas, Napo and Mira rivers, with their respective sub-basins: Rio Guayllabamba, Rio Coca and Rio Mira. In this area a total of 46 micro-basins are distinguished [Moreno et al(2015)Moreno, Luis, Garzón, Gavilanes, Carrera, and Bernal, Burbano et al(2015)Burbano, Becerra, and Pasquel] (see figure 3).

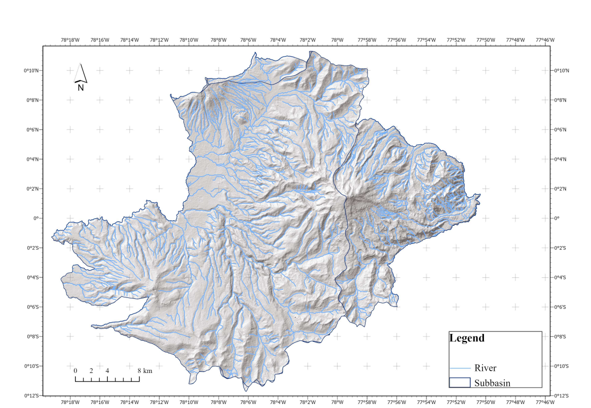

Figure 3: Hydrology of the canton of Cayambe

The water balance calculated from the Olmedo Pichincha Meteorological Station shows that between January-May and October-December rainfall exceeds evapotranspiration. The water shortage occurs between June-September due to the decrease in rainfall in August. Water infiltration ranges from 11.70 to 61.3 mm. The water recharge takes place during the months of February to April and from October to December, with values in the range of 3.41 - 9.16 mm. The annual recharge is 45.03 mm/year [Jiménez(2018)].

The hydrogeology of the canton is represented by the Quito-Machachi hydrogeological unit. This hydrogeological unit covers an area of 3014 Km^2 within whose limits are the valleys of Machachi, Sangolqui, Amaguaña, Tumbaco, Guayllabamba, Cayambe and Altiplano de Quito. The Guayllabamba River is the main drainage of the hydrogeological unit, whose main tributaries are the Machángara, San Pedro, Chiche and El Pisque rivers [Moreno et al(2015)Moreno, Luis, Garzón, Gavilanes, Carrera, and Bernal, Burbano et al(2015)Burbano, Becerra, and Pasquel].

The Quito-Machachi hydrogeological unit represents an elongated graben interrupted by two mountain ranges. The depression is characterized by modern volcanic deposits and rocks that settle in Paleozoic and Mesozoic formations. The geology of this unit consists of modern volcanic deposits and rocks that cover older formations. Taking into account the lithological characteristics, the aquifer systems combined with consolidated and unconsolidated pyroclastic rocks from the Pliocene and Quaternary were distinguished, which are found in the Machachi, Los Chillos, Quito and Cayambe valleys [Burbano et al(2015)Burbano, Becerra, and Pasquel].

In general, 44% of the water flow of the hydrogeological unit corresponds to flows of 1 to 10 l/s, 35% to between 10-30 l/s, a well with a flow of 120 l/s was identified. In the Pisque river valley, the infiltration rate ranges between 3.5 and 5.3 m^2/s. The mean values of electrical conductivity, pH and temperature of groundwater are 514.9 μSm / cm, 6.1 and 17.1 °C, respectively [Burbano et al(2015)Burbano, Becerra, and Pasquel].

The aquifer located between the Cayambe and Pedro Moncayo cantons is currently exploited by 67 wells [Jiménez(2018)]. The groundwater study shows that the iron, manganese and nitrite content of the aquifers located in the northeastern part of the canton is close to the permissible limits. However, these aquifers are very vulnerable to contamination due to the intensive floriculture that takes place in the territory. The groundwater in this part of the canton is used for both human consumption and irrigation [Arciniegas and Sánchez(2003)].

Geological Characteristics of Soil Engineering

At the national level, it has been identified that in the inter-Andean region (1500-3840 meters above sea level), the sand content is higher in urban settlements, while the silt content ranges between 32-47% in the first three soil horizons, with very low values in the fourth horizon (1.7-4%) and it is rich in humus (25%). This percentage of silt increases again at the fifth horizon, which is part of another older volcanic layer. The texture of these soils is silty-sandy in the first three soil horizons [García and Schlatter(2012)].

The organic matter of the territory decreases with altitude. Between 1500-3840 meters above sea level the soil has a greater water retention capacity, but the water capacity for exploitation and consumption is low due to the low level of silt and clay and the coarse porosity of sandy soils. The soils of this region present a weak structure of sub-angular blocks of various sizes in horizons with silty-sandy soils and loose sand grains, which facilitates aeration. In general, the inter-Andean soils are less eroded, richer in organic matter; although average precipitation results in greater leaching [García and Schlatter(2012)].

The predominant soils in the canton of Cayambe are Molizoles (32.07%) that are distributed mainly along the previous contour of the Cayambe volcano, followed by andisols (24.69%), entisols (3.76%) and inceptisols (1.88%). [Moreno et al(2015)Moreno, Luis, Garzón, Gavilanes, Carrera, and Bernal, García and Schlatter(2012), Moreno and Lasso(2013)].

Current geological processes

The Cayambe canton is subject to various geological processes, including landslides; its development is due to a series of factors that influence both independently and jointly on the soil. These events are associated with anomalous hydrometeorological phenomena and seismic phenomena, and to a lesser extent with volcanism. Landslides create dangerous events not only for the population, but also for the infrastructure. The greatest impacts occur on the roads that border the mountains, where the stability of the slopes is reduced. The cost of stabilizing the slopes is high, so that the country's roads generally do not have such infrastructure, with some exceptions [Dávila et al(2018)Dávila, Cuesta, Villagómez, Fierro, León, Guerrero, and Vallejo].

Different factors influence the manifestation of these processes, among them: the degree of inclination of the slope, the type of soil, the length of slopes, the main geological formations, the amount of precipitation (number and annual distribution), the presence of faults, earthquakes, as well as some anthropogenic actions [Dávila et al(2018)Dávila, Cuesta, Villagómez, Fierro, León, Guerrero, and Vallejo].

Estimation of the location of the manifestations of the landslide processes

Landslide inventories can be developed from field studies, by interpreting satellite images, based on spectral characteristics, shape, contrast, and morphological expression, or aerial photographs and interpretation of Google images [Álvarez et al(2020)Álvarez, Oñate-Valdivieso, Esparza, and Oñate-Paladines, Temesgen et al(2001)Temesgen, Mohammed, and Korme, Gond and Brognoli(2005)].

The construction of the landslide inventory was carried out by applying the contrast amplification algorithm proposed by Gond and Brognoli in 2005 and the interpretation of satellite images from the Landsat-8 sensor and Google Earth images. This methodology has proven to be useful for the identification of important changes in vegetation cover, as is the case of gold panning sites within French Guiana. Later it was used to identify landslide scarps in the Mocotíes river basin, Mérida-Venezuela state [Schuster and Highland(2001), Roa(2007), Лебедева, Е. В. and

Михалёв, Д В and Шварев, С В(2015)]. The contrast amplification algorithm is made up of: the vegetation index (NDVI), the leaf tissue moisture index (NDWI), and the mid-infrared (MIR). The spectral bands used, obtained from the Landsat 8 satellite, include: red (RED: 0.64 - 0.67μm), near infrared (Near-Infrared: 0.85 - 0.88 μm) and middle infrared (SWIR 1: 1.57 - 1.65 μm), with a resolution of 30m each. In the equation 1, the normalized difference vegetation index (NDVI) formula is presented.

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

Where:
NDVI Normalized Difference Vegetation Index.
NIR is the near infrared spectral band.
RED is the red spectral band.

In the equation 2, the formula for the composition of the moisture index of foliar tissues is presented..

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \tag{2}$$

Where:
NDWI Normalized Difference Water Index.
NIR is the near infrared spectral band.
GREEN is the green spectral band.

The NDVI and NDWI indices combined with the mid-infrared spectral band, allow to differentiate a high contrast from the numerical values of the satellite image. The widening of contrasts allows to adequately isolate the objects of study by establishing information thresholds. Once the landslides are identified, vectorization is performed to extract useful information. The resulting polygons can be used by different GIS programs.

Assessing susceptibility to landslides

The proposed assessment methodologies are based on the principle that the conditions in which past landslides occurred are the key to the future. The correlation between landslide zones and the associated factors that cause them can be determined by means of the links between the landslide-free zones and the parameters associated with the landslide processes. In this study, eight factors were analyzed to determine the probability of the occurrence of landslides, these factors are: slope, curvature, NDVI, distance to rivers, distance to roads, volcanism and stratigraphic genetic complexes.

Frequency ratio method, FR

The frequency relationship is a simple and useful bivariate statistical method that allows evaluating susceptibility to landslide processes. The frequency relationship methods are based on the observed relationships between the distribution of landslides and each of the selected factors, in order to identify the correlation between the location in which the process occurs and the underlying factors in the study area [Moradi and Rezaei(2014)]. A primary part of the FR methodology is the use of a landslide inventory for analysis.

To determine the "weight" of each factor, first the areas of each class of each factor and their percentages (%) of the study area are calculated. In addition, within each class, the area where the landslides occur (in Km^2 and %) is determined, as well as the relationship between the % of the area of the occurrence of the landslides and the% of the area of the class itself.

In the equation 3, to obtain the Landslides Susceptibility Index (LSI) is presented.

$$LSI = \sum FR_i \tag{3}$$

Analytic Hierarchy Process (AHP)

AHP is a subjective and qualitative model, developed by T. Saati in the 1970s. It is a method for evaluating quantifiable and intangible criteria based on an individual or a group of experts. The AHP method has a multi-use and multi-criteria approach to decision making, which allows the user to obtain scale preferences from a range of alternatives [Moradi and Rezaei(2014), Nicu(2018)].

The evaluation using the AHP method is carried out taking into account the slope inventory map; The researcher identifies the locations of the landslides, the main factors driving the development of landslides, and uses the opinion of experts in the area to reach a conclusion.

To obtain the factor weights in AHP, a pairwise comparison matrix must be constructed with the scores proposed by Saaty on the weighting scale. The weighting scale allows comparing pairs of items that show how much more important or dominant an item is in terms of criteria or property [R.W. Saaty(1987)].

If the coefficient on the vertical axis is more important than the coefficient on the horizontal axis, it varies from 1 to 9. On the contrary, it varies from 1/2 to 1/9.

After calculating the standard weights, consistency was verified by calculating the consistency factor (CR); for this, the consistency index (CI) was determined by 4.

$$CI = \frac{\lambda - n}{n - 1} \tag{4}$$

Where:
CI is the mean vector of the consistency measure.
n is the number of criteria used in the study.

The final consistency coefficient (CR) was calculated dividing CI and RI, as in 5.

$$CR = \frac{CI}{RI} \tag{5}$$

Where:
CI is the consistency index.
RI is the random consistency index.
A matrix with a satisfactory level of consistency should have a CR less than 0.10 to underline the fact that the classification is consistent and reliable; a value greater than 0.1 should be checked in the matrix [Nicu(2018)].

After calculating the weight of each factor and the rate of each class using the AHP method, the LSI is calculated by adding the weight of each factor multiplied by the class weight of each referenced factor (for that pixel) written as follows in equation 6:

$$LSI = \sum_{i=1}^{n} (W_i X R_i) \tag{6}$$

Where:
LSI is the calculated landslide susceptibility index of the given pixel.
R y W are the class classification value.

Results

Estimation of the location of the manifestations of the landslide processes

The contrast amplification methodology was applied to three LANDSAT-8 satellite images, corresponding to the years 2014, 2016 and 2020. The satellite images were obtained from the Earth Explorer portal of the United States Geological Survey, USGS. The projection of the satellite images was carried out in UTM format (Universal Transverse Mercator, 17 S) in the geodetic reference WGS84 (World Geodetic System of 1984)

By comparing the information from the maps obtained from the contrast amplification method with the information stored in Google Earth, a total of 384 landslide processes were identified (figure 4) with a total area of 0.54 Km^2.

Evaluation of susceptibility to landslides

Eight factor maps were used in this study. They are maps of: genetic stratigraphic sequence obtained from detailed geological maps; slopes, curvature, exposure produced from digital elevation model (DEM) data; Normalized Difference Vegetation Index (NDVI) produced from a satellite image; distance to rivers and roads calculated from data obtained from the Military Geographical Institute, IGM; volcanic hazard obtained from the portal of the National Information System, SNI. All data must be converted to raster data based on the attribute data before analyzing it with Spatial Analyst in ArcGIS Pro.

Application of the FR and AHP methodologies to estimate the susceptibility to landslides

Once the FR and AHP methodologies were applied, the coefficients of susceptibility to landslides were obtained for each factor and class (see table 2 in the appendix).

By overlaying the layers in a GIS environment and using relative weights, the final score (LSI) is calculated.

The LSI represents the susceptibility to landslide, the higher value of LSI indicates a greater susceptibility to landslides and if the value is lower it indicates a lower susceptibility to landslides. The LSI values were calculated using equations 3 and 6. From the calculation it was found that the LSI for AHP had a minimum value of 0.03 and a maximum value of 0.32, with an average value of 0.13; while for FR, the minimum value is 2.17 and the maximum is 100.74.

These LSI values were then divided into five classes based on the range of natural breaks (Jenks), representing five different zones on the landslide susceptibility map (see figures 13 and 14).

The susceptibility maps show that both methodologies present similarities in some areas, especially with respect to high and very high levels of susceptibility, however, it is important to highlight that the differences observed are due to the distribution of weights for each factor.

Discussions

Based on the LSI indices, for FR, it is observed that the three main factors for the susceptibility analysis are the stratigraphic genetic complexes, slope and orientation. Within the stratigraphic genetic complex factor, the area occupied by the landslide zone and lake deposits classes are more susceptible to landslides, with LSI values of 44.07 and 39.83, respectively. Secondly, within the "slope" factor, the ranges of 27-37° and greater than 37° show a greater susceptibility to sliding, with LSI values of 4.45 and 2.89. Third, the orientation of the slope, it was determined that the slopes oriented to the southwest, present a greater susceptibility to landslides with an LSI value of 1.27.

The LSI values of the AHP method show that the most relevant factors within the susceptibility analysis

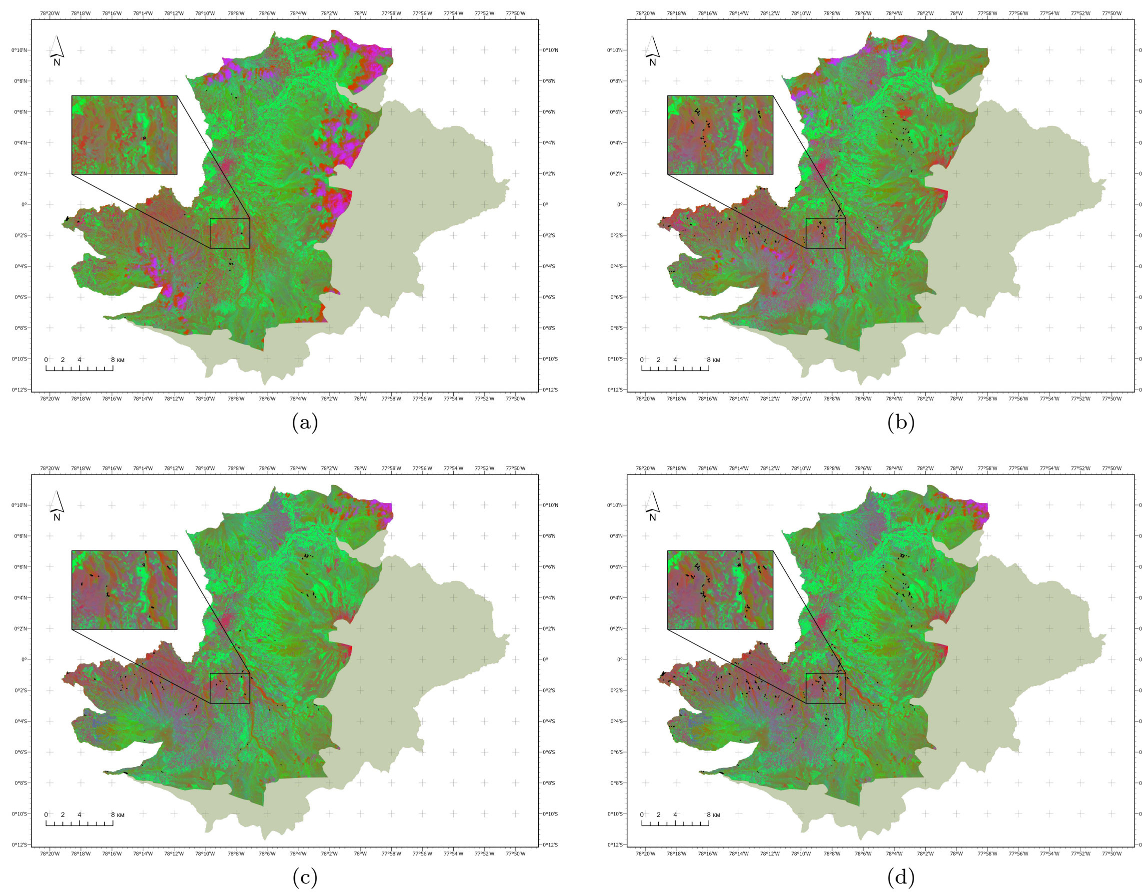

Figure 4: Landslide Inventory Maps: a) 2014; b) 2016; c) 2020; d) final. Areas can be seen in black

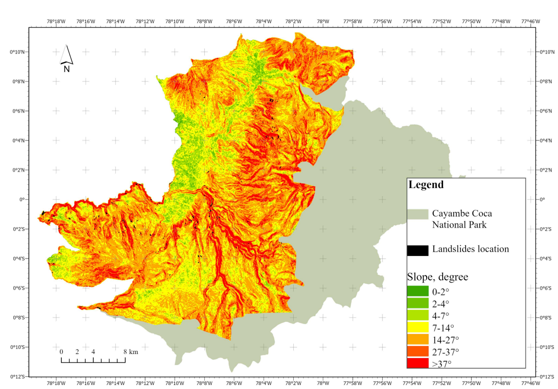

Figure 5: Slope Map

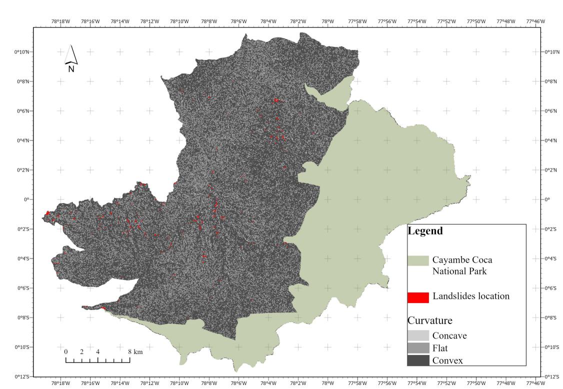

Figure 6: Curvature map

are: slope, orientation and distance to rivers. Within the slope factor, the ranges of 27-37° and greater than 37° show a greater susceptibility to sliding, with LSI values of 0.44 and 0.15. South-facing slopes have a higher probability of landslides, with an LSI value of 0.45. Slopes located at a distance of 500m or less from a body of water present a greater susceptibility to landslides, with an LSI value of 0.63

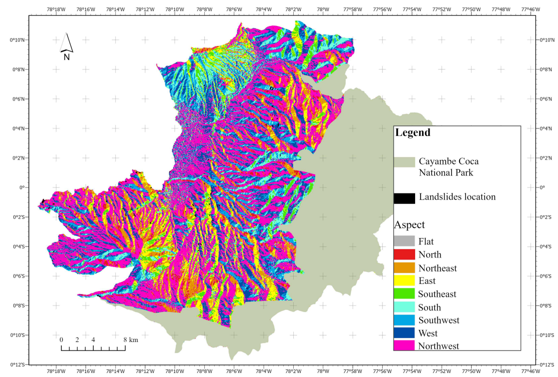

Figure 7: Aspect

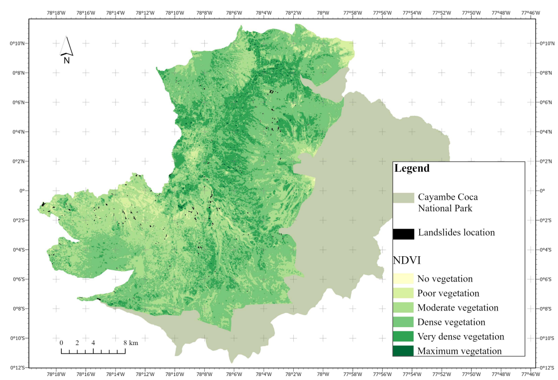

Figure 8: NDVI Map

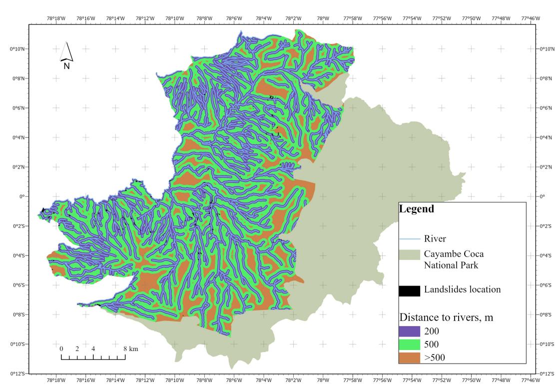

Figure 9: Distance to rivers

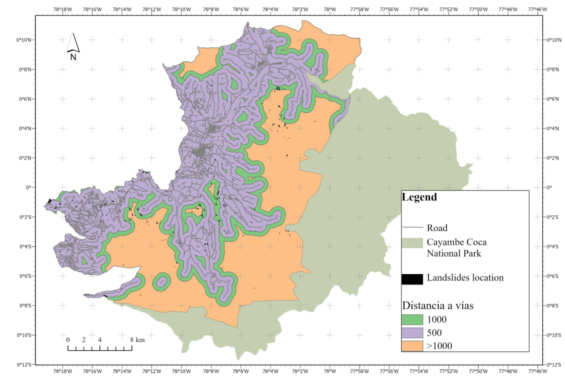

Figure 10: Distance to rivers

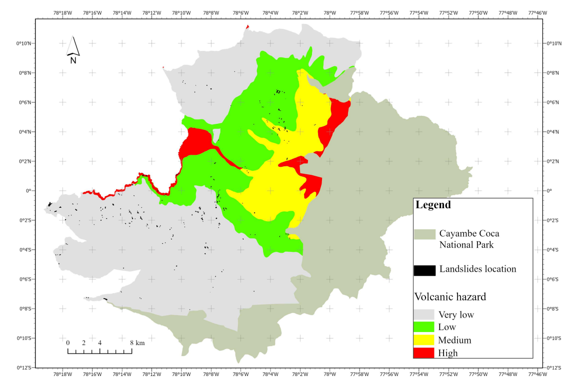

Figure 11: Volcanic hazard map

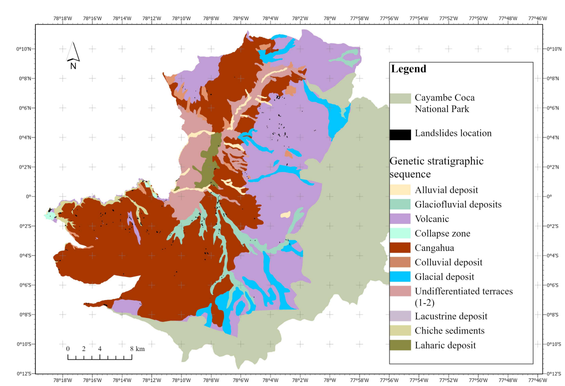

Figure 12: Genetic stratigraphic sequence

Characterization of areas with different degrees of susceptibility to landslides

The interpretation of the data from the FR method shows that the areas with low susceptibility cover approximately half of the study area, with an area of 339.87 Km (44% of the total); while the areas of very low, medium, high and very high susceptibility

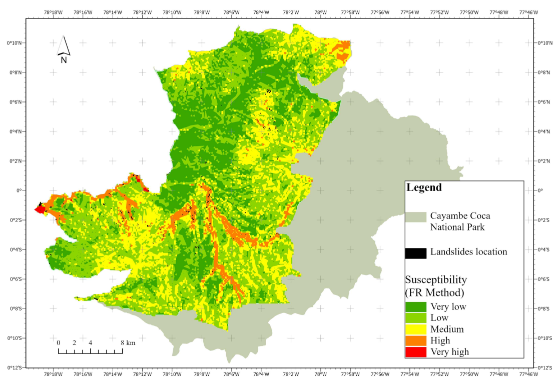

Figure 13: Terrain susceptibility map to landslide processes, FR method

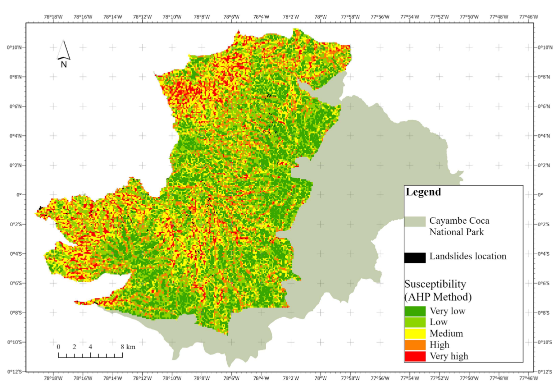

Figure 14: Terrain susceptibility map to landslide processes, AHP method

correspond to 32%, 20%, 4% and 0.2% respectively. Whereas, the data obtained from the AHP method show a more uniform distribution of the zones susceptible to landslide processes, that is, similarities between the zones of low and medium susceptibility (192.81 Km^2 and 193.7 Km^2, respectively); and similarities between the very low and high susceptibility areas (149.22 Km^2 and 143.37 Km^2, respectively), for their part, the very high susceptibility areas cover 98.7 Km^2, which corresponds to 13% of the territory (see figure 15).

The landslides identified in the territory, according to the susceptibility maps created from both methods, are concentrated to a greater extent in the areas with medium susceptibility (see figure 15).

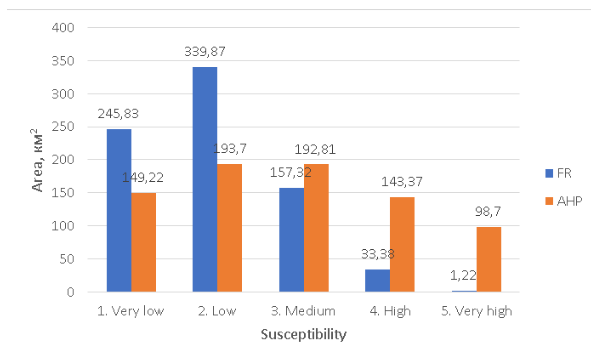

Figure 15: Canton areas with different degrees of susceptibility, Km^2

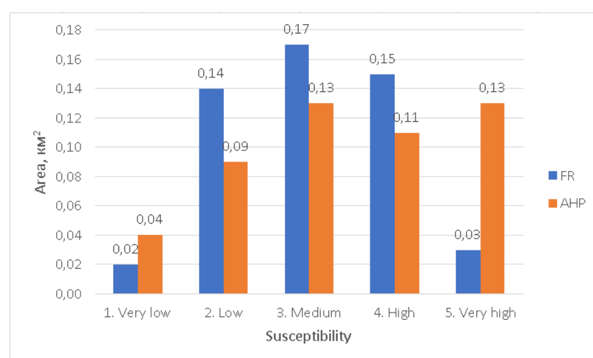

Figure 16: Areas of manifestation of landslide processes according to the degree of susceptibility, Km^2

Landslide distribution by parish

The general analysis of the distribution of landslides by parish shows that rural parishes present a higher concentration of landslides, unlike urban parishes that present a lower density of landslides. In this way, the Cangahua rural parish is the most affected, since it accounts for 42% of the total landslides. To a lesser extent the rural parishes Santa Rosa de Cusubamba and San José de Ayora are affected, with 16% and 13%, respectively (see figure 17).

As a limitation, the study did not include the effects of house loading, impervious terrain surfaces, leaks from water pipes or existing stabilization measures in the calculations.

Conclusions

The calculation of the LSI values for AHP had a minimum value of 0.03 and a maximum value of 0.32, with an average value of 0.13; while for FR, the minimum value is 2.17 and the maximum is 100.74. The LSI values for the FR method show that the three main

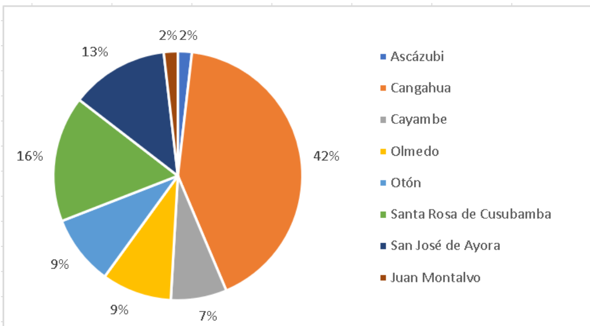

Figure 17: Area of landslide zones by parish

factors for the susceptibility analysis are stratigraphic genetic complexes, slope and orientation. While, the LSI values for AHP, show that the most relevant factors within the susceptibility analysis are: slope, orientation and distance to rivers.

The landslides identified in the territory are concentrated to a greater extent in areas with medium susceptibility. Rural parishes have a higher concentration of landslides, unlike urban parishes that have a lower density of landslides. The Cangahua rural parish is the most affected, since it accounts for 42% of the total landslides.

Appendix

Availability of data and materials
The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. Please contact the corresponding author for data requests.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
GF formulated the problem, carried out preliminary analysis, prepared figures, and drafted the manuscript; LAS carried out statistical analysis, and participated in drafting; JVA compiled landslides data, prepared some of the figures, participated in drafting, and organized the document. All authors read and approved the final manuscript.

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References
Álvarez et al(2020)Álvarez, Oñate-Valdivieso, Esparza, and Oñate-Paladines. Álvarez M, Oñate-Valdivieso F, Esparza C, Oñate-Paladines A (2020) Evaluación multicriterio aplicada al análisis de movimientos en masa en carreteras de montaña: un caso de estudio en los Andes del sur del Ecuador. Avances: Investigación en Ingeniería 17(2):1–13

Arciniegas and Sánchez(2003). Arciniegas S, Sánchez D (2003) Calidad del agua subterránea para el aprovisionamiento del área urbana del cantón Cayambe. Universidad Nacional del Sur, Bahía Blanca, Argentina

Burbano et al(2015)Burbano, Becerra, and Pasquel. Burbano N, Becerra C, Pasquel E (2015) Introducción a la hidrogeología del Ecuador., 2nd edn. Quito

Campo(2003). Campo A (2003) Estudio integrado de la cuenca del río Pisque, cantón Cayambe, Ecuador. In: XXXI Curso Internacional de Geografía Aplicada, organizado por el Centro Panamericano de Estudios e Investigaciones Geográficas (CEPEIGE), Quito, p 16

Daniel et al(2021)Daniel, Ng, Abdul Kadir, and Pereira. Daniel M, Ng N, Abdul Kadir M, Pereira J (2021) Landslide Susceptibility Modeling Using a Hybrid Bivariate Statistical and Expert Consultation Approach in Canada Hill, Sarawak, Malaysia. Frontiers in Earth Science 9:1–15,

Dávila et al(2018)Dávila, Cuesta, Villagómez, Fierro, León, Guerrero, and Vallejo. Dávila Á, Cuesta R, Villagómez M, Fierro D, León F, Guerrero K, Vallejo J (2018) Atlas de espacios geográficos expuestos a amenazas naturales y antrópicas. Instituto Geográfico Militar, Ecuador

Edigbue et al(2021)Edigbue, Al-Mashhor, Plougarlis, Soupios, Tranos, Kaka, Al-Shuhail, and A Edigbue PI, Al-Mashhor AA, Plougarlis A, Soupios P, Tranos M, Kaka SL, Al-Shuhail A, Al-Garni M (2021) Geological and geophysical investigations of an engineering site characterization for construction purposes in Western Saudi Arabia. Journal of Applied Geophysics 188:104,307, , URL https://doi.org/10.1016/j.jappgeo.2021.104307

García and Schlatter(2012). García LC, Schlatter JE (2012) Caracterización de suelos a lo largo de un gradiente altitudinal en Ecuador. Revista Brasileira de Ciências Agrárias 7(3):456 – 464

Gariano and Guzzetti(2016). Gariano SL, Guzzetti F (2016) Landslides in a changing climate. Earth-Science Reviews 162:227–252, , URL http://dx.doi.org/10.1016/j.earscirev.2016.08.011

Getachew and Meten(2021). Getachew N, Meten M (2021) Weights of evidence modeling for landslide susceptibility mapping of Kabi-Gebro locality, Gundomeskel area, Central Ethiopia. Getachew and Meten Geoenvironmental Disasters 8(6):1–22,

Gond and Brognoli(2005). Gond V, Brognoli C (2005) Télédétection et aménagement du territoire : localisation et identification des sites d'orpaillage en Guyane Française. BOIS ET FORÊTS DES TROPIQUES 4(286):5–13

Jelínek and Wagner(2007). Jelínek R, Wagner P (2007) Landslide hazard zonation by deterministic analysis (Veľká Čausa landslide area, Slovakia). Landslides 4(4):339–350,

Jiménez(2018). Jiménez E (2018) Caracterización hidrogeológica y análisis de vulnerabilidad del acuífero de Cayambe, NOR-ESTE de la provincia de Pichincha. PhD thesis, Universidad Central del Ecuador

Moradi and Rezaei(2014). Moradi S, Rezaei M (2014) A GIS-based comparative study of the analytic hierarchy process , bivariate statistics and frequency ratio methods for landslide susceptibility mapping in part of the Tehran metropolis , Iran 4(1):45–61

Moreno and Lasso(2013). Moreno J, Lasso L (2013) Geopedología, instituto edn. Cayambe

Moreno et al(2015)Moreno, Luis, Garzón, Gavilanes, Carrera, and Bernal. Moreno M, Luis J, Garzón M, Gavilanes L, Carrera F, Bernal G (2015) Actualización Del Plan De Desarrollo Y Organización Territorial Del Gobierno Autónomo Descentralizado Intercultural Y Plurinacional Municipal De Cayambe 2015 – 2025. GADIPCayambe, Cayambe

Nicu(2017). Nicu I (2017) Frequency ratio and GIS-based evaluation of landslide susceptibility applied to cultural heritage assessment. Journal of Cultural Heritage 28:172–176, , URL https://www.sciencedirect.com/science/article/pii/S1296207417302054

Nicu(2018). Nicu IC (2018) Application of analytic hierarchy process, frequency ratio, and statistical index to landslide susceptibility: an approach to endangered cultural heritage. Environmental Earth Sciences 77(3):1–16, , URL https://doi.org/10.1007/s12665-018-7261-5

Norma Ecuatoriana de la Construcción(2014). Norma Ecuatoriana de la Construcción (2014) Peligro sísmimo. Diseño sismo resistente

Ortega(2012). Ortega A (2012) Análisis de riesgos naturales en la subcuenca del río Blanco, desde su origen hasta la ciudad de Cayambe, provincia de Pichincha. PhD thesis, Universidad San Francisco de Quito

Paudel et al(2016)Paudel, Oguchi, and Hayakawa. Paudel U, Oguchi T, Hayakawa Y (2016) Multi-Resolution Landslide Susceptibility Analysis Using a DEM and Random Forest. International Journal of Geosciences 7(5):726–743, , URL https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/journal/paperinformation.aspx?paperid=66885

Pourrut(1983). Pourrut P (1983) Los climas del Ecuador: fundamentos explicativos. Centro Ecuatoriano de Investigaciones Geográficas pp 7–41, URL http://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers11-10/21848.pdf

Puente et al(2021)Puente, Egas, and Teller. Puente F, Egas A, Teller J (2021) Land policies for landslide risk reduction in Andean cities. Habitat International 107:1–15, , URL https://www.sciencedirect.com/science/article/pii/S0197397520314223

Roa(2007). Roa J (2007) Estimacion de áreas susceptibles a deslizamientos mediante datos e imágenes satelitales: cuenca del río Mocotíes, estado Mérida-Venezuela. Revista Geográfica Venezolana 48(2):183–219

R.W. Saaty(1987). RW Saaty (1987) THE ANALYTIC HIERARCHY PROCESS-WHAT IT IS AND HOW IT IS USED. Mat/d Modelling 9(3-5):161–176, URL https://core.ac.uk/download/pdf/82000104.pdf

Sanchez and Castro(2008). Sanchez L, Castro M (2008) Pérdidas por desastres de impacto extremo, grande y menor en Ecuador, 1970 – 2007. In: Corporación OSSO (ed) Creación, actualización y/o homogeneización de inventarios de desastres por eventos históricos y cotidianos a nivel de la Subregión Andina, Comunidad Andina, Cali, p 47, URL http://www.comunidadandina.org/predecan/doc/r2/osso/Cons025-2006-CorporacionOSSO-Articulo-Ecuador.pdf

Schuster and Highland(2001). Schuster R, Highland L (2001) Socioeconomic and Environmental Impacts of Landslides in the Western Hemisphere. Tech. rep., U.S. Geological Survey, Denver, Colorado, URL https://pubs.usgs.gov/of/2001/0276/report.pdf

Tan et al(2021)Tan, Bai, Zhou, Hu, and Qin. Tan Q, Bai M, Zhou P, Hu J, Qin X (2021) Geological hazard risk assessment of line landslide based on remotely sensed data and GIS. Measurement 169:1–10, , URL https://www.sciencedirect.com/science/article/pii/S0263224120309064

Temesgen et al(2001)Temesgen, Mohammed, and Korme. Temesgen B, Mohammed M, Korme T (2001) Natural hazard assessment using GIS and remote sensing methods, with particular reference to the landslides in the Wondogenet Area, Ethiopia. Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science 26(9):665–675, , URL https://www.sciencedirect.com/science/article/pii/S1464191701000654

Van Westen and Terlien(1996). Van Westen C, Terlien M (1996) AN APPROACH TOWARDS DETERMINISTIC LANDSLIDE HAZARD ANALYSIS IN GIS. A CASE STUDY FROM MANIZALES (COLOMBIA). Earth Surface Processes and Landforms 21(9):853–868

Лебедева, Е. В. and Михалёв, Д В and Шварев, С В(2015). Лебедева, Е В and Михалёв, Д В and Шварев, С В (2015) Напряженность геоморфологических обстановок центрального сектора горной системы Анд. Геоморфология pp 77–88

Позаченюк Е. А. Петлюкова Е. А.(2016). Позаченюк Е А Петлюкова Е А (2016) Гис-анализ морфометрических показателей рельефа центрального предгорья главной гряды крымских гор для целей ландшафтного планирования

Симонян, В.В.(2011). Симонян, ВВ (2011) Изучение оползневых процессов геодезическими методами. PhD thesis, Моск. гос. строит. ун-т.

Tables

Table 2: Results of the determination of the "weight" of the factors that lead to the development of the slope processes by FR and AHP

Factor	Class	Class Area		Landslide area		FR	AHP	AHP Class
		Km^2	%	Km^2	%			
Curvature	Concave	370,73	47,22	0,23	41,94	0,89	0,10	0,08
	Flat	36,26	4,62	0,02	3,41	0,74	0,26	
	Convex	378,14	48,16	0,29	54,65	1,13	0,64	
Exposition	Flat (-1)	0,20	0,03	0,00	0,00	0,00	0,00	0,20
	North	117,78	15,07	0,07	13,16	0,87	0,03	
	Northeast (22.5-67.5)	97,42	12,46	0,08	15,23	1,22	0,03	
	East (67.5-112.5)	61,38	7,85	0,05	9,59	1,22	0,08	
	Southeast (112.5-157.5)	49,84	6,38	0,02	3,38	0,53	0,12	
	South (157.5-202.5)	71,11	9,10	0,03	5,83	0,64	0,45	
	Southwest (202.5-247.5)	113,31	14,49	0,10	18,42	1,27	0,17	
	West (247.5-292.5)	138,42	17,71	0,10	19,55	1,10	0,06	
	Northwest (292.5-337.5)	132,32	16,93	0,08	14,85	0,88	0,05	
Distance to rivers, m	200	396,70	50,49	0,45	84,10	1,67	0,63	0,14
	500	296,23	37,70	0,08	14,55	0,39	0,22	
	>500	92,80	11,81	0,01	1,35	0,11	0,15	
Distance to roads, m	500	373,36	47,54	0,28	51,43	1,08	0,49	0,12
	1000	106,54	13,56	0,16	28,89	2,13	0,31	
	>1000	305,51	38,90	0,11	19,68	0,51	0,20	
Slope, grades	0-2°	21,50	2,74	0,00	0,00	0,00	0,04	0,32
	2-4°	52,18	6,65	0,00	0,00	0,00	0,05	
	4-7°	98,44	12,54	0,00	0,00	0,00	0,07	
	7-14°	225,24	28,69	0,05	8,44	8,44	0,10	
	14-27°	269,86	34,37	0,23	42,41	1,23	0,15	
	27-37°	88,86	11,32	0,18	32,68	2,89	0,15	
	>37°	29,05	3,70	0,09	16,48	4,45	0,44	
NDVI	-0,31 - 0	0,18	0,02	0,00	0,00	0,00	0,40	0,05
	0 - 0,15	49,19	6,26	0,10	17,84	2,85	0,21	
	0,15 - 0,30	316,08	40,25	0,38	70,45	1,75	0,16	
	0,30 - 0,45	350,44	44,62	0,06	10,97	0,25	0,13	
	0,45 - 0,60	68,67	8,74	0,00	0,74	0,09	0,06	
	0,60 - 0,67	0,80	0,10	0,00	0,00	0,00	0,04	
Volcanic hazard	Very low	467,773	59,56	0,35	64,22	1,08	0,41	0,06
	Low	186,66	23,77	0,14	25,24	1,06	0,26	
	Medium	96,09	12,23	0,04	6,52	0,53	0,22	
	High	34,88	4,44	0,02	4,02	0,90	0,10	
Genetic stratigraphic sequence	Volcanic	263,80	33,59	0,14	26,68	0,79	0,19	0,03
	Chiche sediments	8,44	1,07	0,04	8,17	7,60	0,13	
	Glaciofluvial deposits	34,36	4,37	0,10	19,30	4,41	0,14	
	Cangahua	341,48	43,48	0,18	33,26	0,77	0,10	
	Collapse zone	1,46	0,19	0,04	8,19	44,07	0,12	
	Undifferentiated terraces (1-2)	61,78	7,87	0,00	0,37	0,05	0,09	
	Laharic deposits	10,75	1,37	0,01	1,30	0,95	0,06	
	Lacustrine deposits	0,03	0,00	0,00	0,15	39,83	0,07	
	Colluvial deposits	9,79	1,25	0,00	0,00	0,00	0,05	
	Alluvial deposits	7,72	0,98	0,01	2,16	2,20	0,03	
	Glacial deposits	45,78	5,83	0,00	0,41	0,07	0,02	