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ОПРЕДЕЛЕНИЕ ЗОН ОПОЛЗНЕВОЙ ОПАСНОСТИ МЕТОДОМ АНАЛИЗА ИЕРАРХИЙ НА ПРИМЕРЕ ПРОВИНЦИИ ГУАНТАНАМО

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Аннотация: Создание прогнозных моделей для определения районов оползневой опасности важно для своевременного принятия мер в целях предотвращения катастроф, связанных с оползневыми явлениями. Настоящее исследование, проведенное в провинции Гуантанамо на Кубе, имело основной целью определение зон с разной вероятностью схождения оползней. Применялся метод многокритериального принятия решений, использованный Саати (1980), с учетом следующих факторов: угол наклона, высота над уровнем моря, расстояние до рек, расстояние до разлома, расстояние до дорог, среднегодовое количество осадков, литология, мощность, тип и механический состав почвы, а также наличие растительности. Весовые коэффициенты факторов были определены с помощью метода анализа иерархий (МАИ), а рейтинги классов факторов были присвоены путем логического суждения. Индексы вероятности для оползневой опасности определялись на основе непрерывной числовой шкалы, разработанной для этой цели. Было установлено, что зоны высокой и умеренной вероятности соответствуют северо-востоку провинции Гуантанамо, для которой характерны высокая плотность разломов и гидрологической сети и маломощные глинистые грунты. В этой зоне также представлены в основном породы метаморфического и офиолитового комплексов, в целом, с сильно нарушенной структурой. Кривая операционных характеристик приемника (ROC) показала приемлемые результаты. Кроме того, оценка риска показала высокие или очень высокие риски для населения этих районов.

Ключевые слова: метод анализа иерархий (МАИ), Гуантанамо, зонирование районов оползневой опасности, Куба, оползни, гравитационные процессы, оползневая опасность, шкала важности Саати.

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Landslide susceptibility zonation using the analytical hierarchy process. A case study of Guantanamo Province

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Abstract: The creation of predictive models to determine areas susceptible to landslides is important for timely management towards disaster prevention of these phenomena. The present study in the province of Guantanamo in Cuba had as main objective the landslide susceptibility zonation (LSZ). The multicriteria decision method used by Saaty (1980) was adopted, considering the factors; slope angle, elevation, distance to rivers, distance to fault, distance to roads, average annual rainfall, lithology, soil depth, soil type, texture and vegetation. Factor weights were determined through the Analytical Hierarchy Process (AHP) and factor class ratings were assigned through logical judgment. Landslide susceptibility indices were determined based on a continuous numerical scale developed for this purpose. It was found that the zones of high and moderate susceptibility corresponded to the northeast of the Guantánamo province, which are characterized by a high density of faults and the hydrological network, shallow soils with clayey composition. This zone is also constituted fundamentally by rocks of the metamorphic and ophiolitic complexes, in general, very structurally affected. The receiver operating characteristic (ROC) curve showed acceptable results. In addition, the risk assessment indicated that populations at high to very high risk.

Key words: Analytical Hierarchy Process (AHP), Guantanamo, landslide susceptibility zonation, Cuba, landslides, gravitational processes, landslide hazard, nine-point importance scale, according to Saaty.

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Introduction

In the Latin American and Caribbean region, geological processes, especially landslides, represent one of the most dangerous geological processes related to exogenous geodynamic processes [1—2]. These phenomena make a significant contribution to the evolution of the relief and landscape of the Earth's surface in many areas, drastically change the conditions of the geological environment, and are among the most damaging geological hazards in the world. Landslides threaten to create extreme vulnerability to cities and ecosystems [3—5], which is aggravated by the evolution of demographic conditions, driven by uncontrolled urbanization and the increase in anthropic pressures in high-risk areas [6], environmental degradation and change global climate [7—9].

At the international level, numerous studies of landslide phenomena are carried out, mainly focused on the study of factors that determine the susceptibility of the geological environment to these phenomena [10—12].

It should be noted that all these studies are based on the development of prediction models to determine the susceptibility of the land to landslides, based on topographic, geomorphological, lithological, land use data, geomechanical properties of rocks, hydrogeological and hydrological conditions between others [13—17]. These factors are directly related to the deformations that occur in rock masses [18—22]. Other authors have considered in their studies that factors such as proximity to faults and lineaments, proximity to bodies of water and construction activities, particularly roads, are important elements that can contribute to the occurrence of landslides [23—25]. In addition to the conditioning factors, other authors have considered the so-called trigger factors such as rainfall [26–30].

There are many modeling techniques and approaches to assessment landslide susceptibility [31, 32]; although there is no majority consensus on the effectiveness of one over the other, the susceptibility assessment using AHP is one of the most used by authors to analyze susceptibility to landslides [33–35]. The AHP is a technique considered as a pairwise matrix analytical process used by Saaty [36] to know the weight and geometric mean of the different parameters. Many researchers used the AHP technique to assign weight to criteria and sub-criteria based on expert knowledge and experiences [37–39]. Many applications have been reported from various parts of the world [40, 41].

Study area

The study area corresponds to the province of Guantánamo, which is located in the eastern part of the island of Cuba, delimited by latitude 20°8'39.98. N and longitude 75°12'33.01" O. It has limits to the north with the province of Holguín, to the south with the Caribbean Sea, to the west with the province of Santiago de Cuba and to the east with the Paso de los Vientos and covers an area of 6,178 km^2, which represents 5.6% of the total area of the Cuban archipelago (Fig. 1). This province is characterized by having one of the most

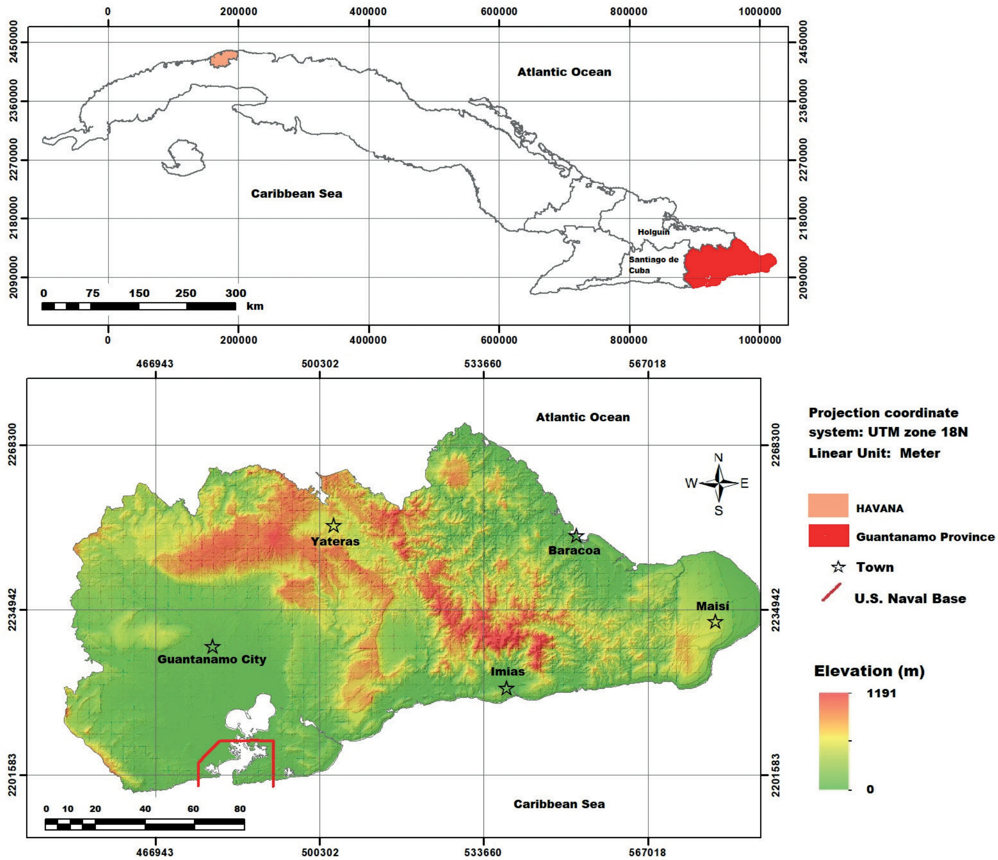

Fig. 1. Location map of the study area
Рис. 1. Карты района исследования

vigorous reliefs in our country and where around 75% of its territory is part of the Nipe-Sagua Baracoa mountain range.

Geology

The study area is very complex from a geological and structural point of view due to the occurrence of a set of tectonic episodes that have overlapped and have considerably affected the distribution of rock complexes that affect the properties of the rocks present and therefore the quality of rock complexes. In the geological evolution of the study area, its rocks have been subjected to various processes that have led to the formation of 4 fundamental rock complexes: metamorphic complex, which presents the oldest rocks, with different degrees of weathering and high deformation mainly constituted by green schists of volcanic rocks [42]. These rocks are metamorphosed under conditions of very low grade and high pressure. The main geological formation in this complex, due to its great extension and the lithological and structural complexity it presents, is the Sierra del Purial Formation, mainly composed of schists.

Towards the center and north of the study area, the ophiolitic complex is developed with a predominance of rocks from an ancient oceanic crust with hazburgites, lherzolites, and serpentine dunites as the main rocks. The Paleogene Island Arc rock complex is characterized by its low complexity from a structural point of view and its homogeneity from a lithological point of view, and is mainly made up of tuffs. Finally, there are the rocks of the cover. Composed of sedimentary rocks with a wide distribution, which generally present smooth folds of wide radius and the stratification is quite horizontal. The oldest rocks have been more exposed to different tectonic processes that have affected the quality of the rock masses.

Materials and methods

In the present study, the Analytical Hierarchy Process (AHP) technique, proposed by Saaty (1980), was applied to evaluate landslide susceptibility zoning

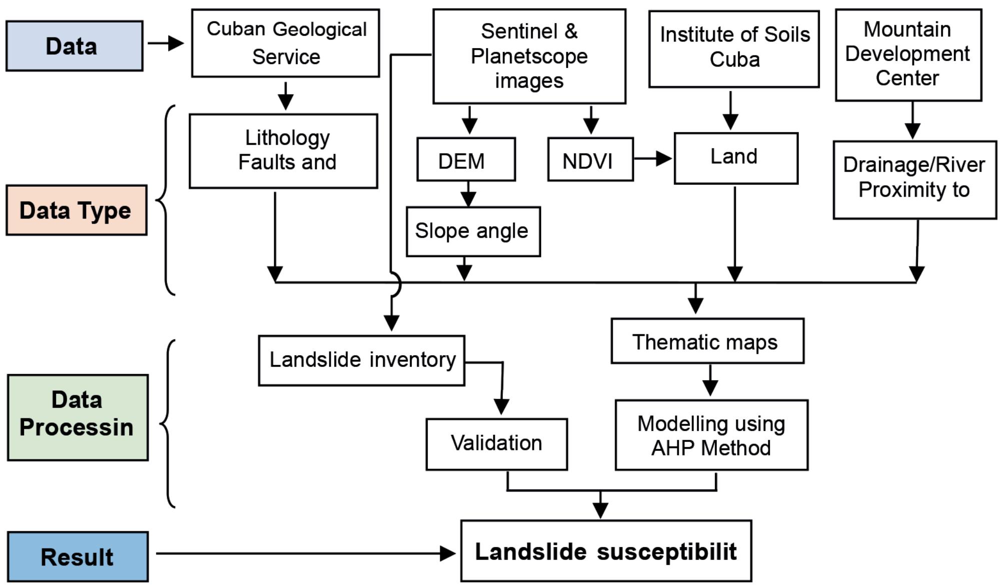

Fig. 2. General methodology followed in the present study
Рис. 2. Общая методология исследования

in the area. In this technique, the method of weighted sum of factors is used, taking into account ten factors that have an impact on the occurrence of this type of phenomenon in the Guantanamo province to create thematic maps. A hierarchy of conditioning factors was used, making a comparison between pairs through a matrix; Subsequently, weights were assigned for each factor and a consistency relationship that quantifies the ambiguity in the analysis [36, 43]. Fig. 2 shows the methodology followed for the study.

Dataset

Different data sources were used for the creation of the thematic layers (Table 1). The geological map at a scale of 1:100,000 from the Institute of Geology and Paleontology and the soil parameters (depth and soil texture) at a scale of 1:100,000 from the Institute of Soils of Cuba were included in the analysis.

Conditioning factors

The conditioning factors used for the AHP decision-making process were; slope angle, elevation, distance to river, lithology, distance to faults, soil depth and texture, distance to road, vegetation, and average annual rainfall. This approach is convenient and effective for landslide susceptibility studies. As a limitation, we can consider that the type of failure and earthquakes are not included as the trigger factor in the analysis, which can lead to significant uncertainties.

The main geological formations that have a lithological behavior susceptible to the occurrence of landslides were defined using morphometric and structural criteria. The soil map was used according to the UCS Unified Soil Classification System classification, since it better adapts to engineering-geological criteria. The Sentinel satellite images of the years 2016 and 2017 were processed with which the normalized

Table 1

List of data and data sources used in the study
Список данных и источников данных, использованных в исследовании

Data	Description	Source
Digital Elevation Model (DEM) (resolución 12,5 m)	Derived from Sentinel images	https://www.esa.int/
Slope inclination (°)	Derived from MDT 12,5 m	Sentinel images
Elevation (m)	Derived from MDT 12,5 m	Sentinel images
Lithology	Geologic map in vector format	Institute of Geology and Paleontology / Cuban Geological Service
Faults and lineament	Geologic map in vector format	Institute of Geology and Paleontology / Cuban Geological Service
Soil properties (depth and texture)	Soil map in vector format	Institute of Soils Cuba
Vegetation/NDVI	Derived from Sentinel images	https://www.esa.int/
Proximity to river	River map in vector format	Mountain Development Center, Cuba
Proximity to roads	Roads map in vector format	Mountain Development Center, Cuba
Rainfall	Rainfall map in raster format	
Landslide Inventory	Point data on past landslides digitized from previous study	Previous landslide inventory map [42]

Table 2

Nine-point importance scale, according to Saaty (1980) [36]
Шкала важности Саати (1980) [36]

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very Strongly	Extremely
Less important						Very important		
Intermediate values				→ (2,4,6,8)		Preference made halfway		

vegetation index was calculated for both moments and by subtraction of images the change of use model was obtained for areas with slopes greater than 10 degrees, which are the more susceptible to the occurrence of the phenomena analyzed.

The thematic layer of roads from the Mountain Development Center belonging to the Cuban Environment Agency was used. Buffer analyzes were carried out to know the zones of influence with respect to the zones with the occurrence of landslides. The hydrographic network of the study area is one of the densest in the country, for which reason the permanent channels were selected and a buffer analysis was carried out at 500 m.

Landslide susceptibility evaluation

The Analytical Hierarchy Process (AHP) is one of the GIS-based techniques applied to landslide susceptibility zoning [44—46]. The objective of the technique is to obtain a landslide susceptibility index (LSI), based on expert judgments expressed through pairwise comparisons using a preference scale, which allows the generation of priority scales.

In order to understand the relative contributions of these conditioning factors, in inducing land susceptibility to landslides, the different factors were ranked and a comparison was made between pairs. The pairwise comparison was based on expert judgment, where the relative influence of factors on the occurrence of landslides was considered. Finally, they provided the corresponding weights for each of the conditioning factors analyzed. The standard scale that was followed to carry out the comparisons by pairs was proposed by Saaty [47, 48] (Table 2).

The weights for each causative factor and a consistency ratio (*CR*) that quantifies the unambiguity for the pair-wise comparison were worked out (Saaty, 1980) [36].

The consistency ratio (*CR*) is defined as the ratio in between the consistency index (*Ci*) and the random index (*Rci*) computed from a large number of randomly generated positive reciprocal matrices of order *n* [48]. Equation (1) *CR* is calculated using equation (2).

$$CR = Ci / Rci, \qquad (1)$$

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \qquad (2)$$

where ‘$\lambda_{\max}$’ refers to maximum eigen value of composition matrix and ‘*n*’ is the order of composition square matrix.

The random index (*Rci*) is calculated using equation (3)

$$Rci = \frac{1{,}98 * (n - 2)}{n}. \qquad (3)$$

The priority vector is considered to have an acceptable inconsistency when the *CR* is less than 10% [36, 49].

Landslide susceptibility mapping was performed considering the primary weights assigned to the respective conditioning factors using the AHP method (Table 3); the respective ranges for each class of fac-

Table 3

Conditioning factors with their classes and ranges regarding their influence on the occurrence of landslides

Обуславливающие факторы, их классы и диапазоны их влияния на возникновение оползней

Conditioning factor	Factor Class	Rank	Importance for instability
Slope angle (°)	0 – 14	1	Low
	14 – 22	2	Medium
	22 – 32	3	High
	32 – 69	4	Very high
Elevation (m)	0 – 126	1	Very low
	126 – 289	2	Low
	289 – 462	3	Médium
	462 – 649	4	High
	649 – 1191	5	Very hugh
Distance to fault (m)	> 3000	1	Low
	2000 – 3000	2	Medium
	2000 – 1000	3	High
	< 1000	4	Very high
Distance to river (m)	> 800	1	Low
	500 – 800	2	Medium
	200 – 500	3	High
	< 200	4	Very high
Distance to road (m)	> 1000	1	Low
	500 – 1000	2	Medium
	> 500	3	High
Soil depth	Shallow	1	Low
	Médium Deep	2	Medium
	Deep	3	High
	Very deep	4	Very high
Soil type	Humic, Histosol, Saline	1	Low
	Fluvisol, Lithosol	2	Medium
	Brown, Ferritic	3	High
	Ferralitic, Ferralic, Fersialitic	4	Very high
Lithology	Sedimentary cover	1	Low
	Paleogene complex	2	Medium
	Ophiolitic complex	3	High
	Metamorphic complex	4	Very high
Vegetation/NDVI	> 1.722	1	Low
	– 0.149 – (–2.022)	2	Medium
	< –2.022	3	High
Average annual rainfall (mm)	< 400	1	Low
	400 – 1000	2	Medium
	1000 – 2000	3	High
	> 2000	4	Very high

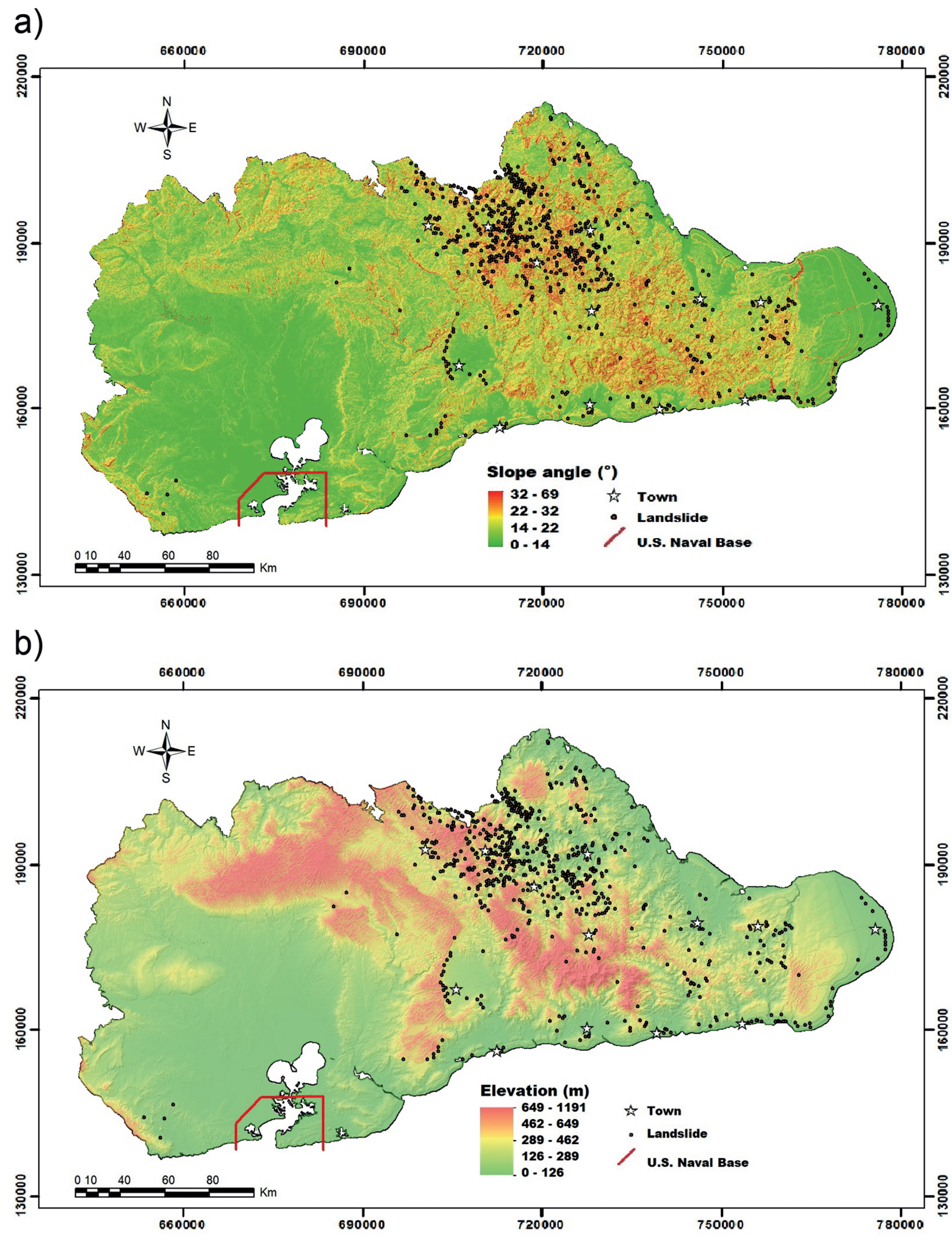

Fig. 3. Maps of topographic factors that make the study area susceptible to the occurrence of landslides: Slope angle (a), Elevation (b)

Рис. 3. Топографические факторы, способствующие возникновению оползней на изучаемой территории: угол наклона (а) и высота над уровнем моря (б) tor were made through a logical judgment based on knowledge where the qualification is based on the influence of the factor in inducing instability to the ground (Table 2). A continuous scale of numerical values was determined as a landslide susceptibility index (LSI) [45] using the equation (4), which was used for the construction of the landslide susceptibility map to.

$$LSI = \sum_{i=1}^{n} R_i \times w_i \,, \qquad (4)$$

where R_i is the respective rating for each conditioning factor class and w_i is the weight for corresponding considered conditioning factors.

Results and discusión

In the study, all the ranges for the conditioning factors involved were established, which are shown in Table 3. In the analysis, each one of the thematic maps was validated with the inventory of landslides [42].

Topographic factors

The characteristics in the topography is an important conditioning factor that influences the instability of the slopes. Its features can be spatially represented using the digital elevation model (DEM). The main topographic characteristics that were considered in the landslide susceptibility study were: slope angle and elevation. The slope angle map for the study area was derived from DEM in degree values ranging from 0 to 69°. Furthermore, the slope angle was reclassified into four classes, as shown in Table 3: (i) gentle slopes, 0—14°, (ii) moderately steep slopes, 14—22°, (iii) steep slopes, 22—32°, and (iv) very steep slopes 32—69° (Fig. 3, a and Table 3).

By corroborating the reclassification with the inventory, it was determined that the slope angle class most susceptible to landslides is considered to be very steep slopes (32—66°) (Fig. 3, *a*). The elevation of the study area varies between 0 and 1191 m above sea level; the elevation was reclassified in 5 class as shown in Table 3; the elevation had little significant difference, because there is a wide distribution of landslides in all ranges (Fig. 3, *b*).

Lithology, fault and soil properties

In the present study, lithology, distance to fault, soil depth, and type were considered conditioning factors that have possibly influenced landslides in the study area.

The lithology was reclassified into four classes taking into account the formations that constitute the different rock complexes. In the thematic map of the lithology of Fig. 4, *a*, the largest number of inventoried landslides are distributed in more than 70% in the metamorphic complex generally composed of volcanic rock schists and in the ophiolitic complex constituted by remains of the crust. oceanic. The study area is highly affected from a structural point of view. By buffering the distance to fault thematic layer, this layer was reclassified into four classes that established the following ranges of proximity to faults: (i) < 1000 m, (ii) 1000—2000 m, (iii) 2000—4000 m and (iv) > 4000 m; It was found that most of the landslides are located in areas less than one kilometer from the faults (Fig. 4, *b*).

The type of soil was reclassified into four classes (Table 3). A high number of landslides was identified in the ranges of high and very high importance for instability represented by brown, ferralitic, ferritic, ferralic and fersialitic soils (Fig. 4, *c*), whose genesis comes from the rocks of the metamorphic and ophiolitic complex. These rocks have a clay loam, sandy loam and sandy texture. The depth of the soils was reclassified into four classes (Fig. 4, *d*, Table 3). However, when corroborating with the inventory, it was determined that it does not present a significant incidence because landslides have a wide distribua)

b)

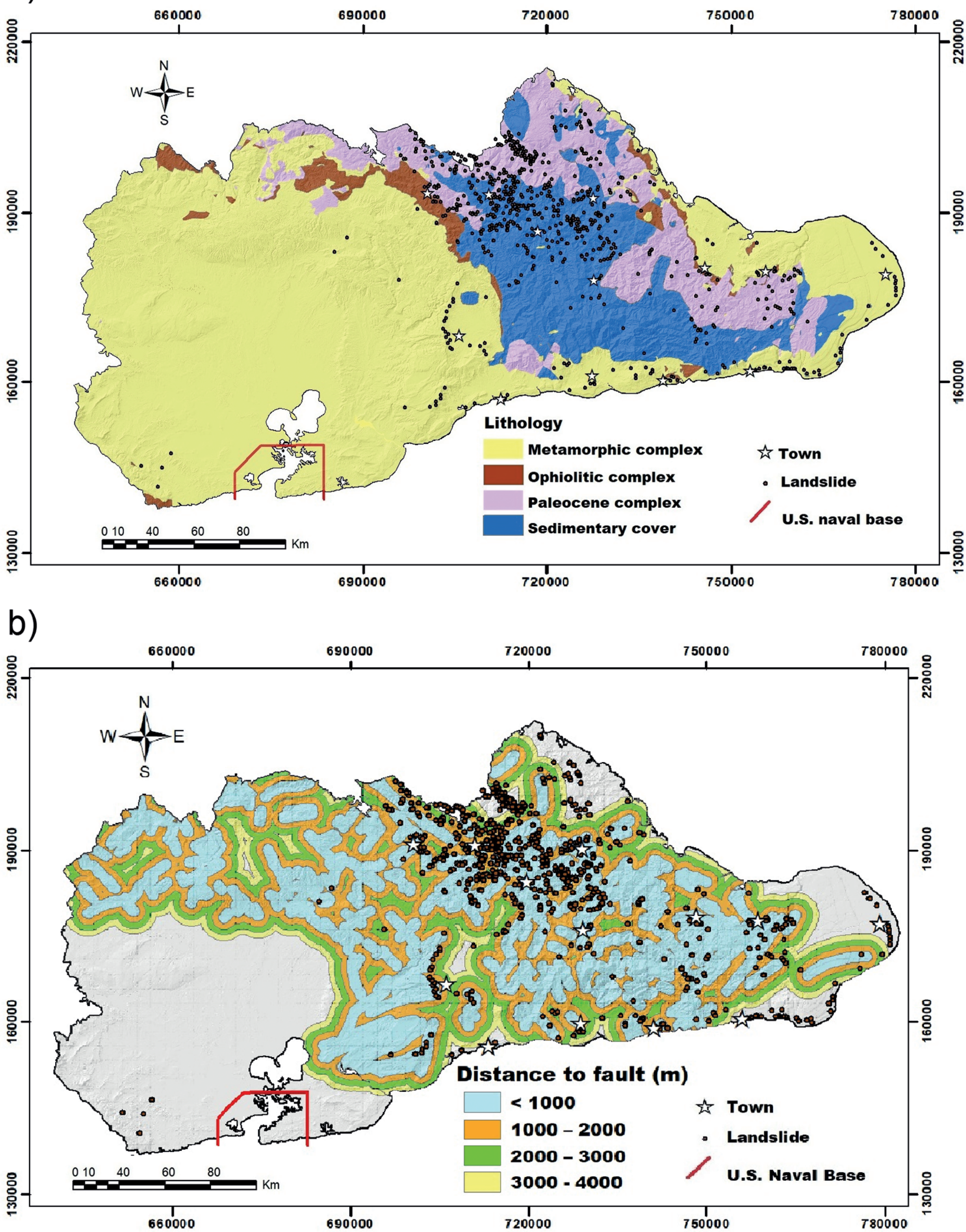

Fig. 4. Maps of conditioning factors that make the study area susceptible to the occurrence of landslides: Lithology (a), Distance to fault (b)

Рис. 4. Карты обуславливающих факторов оползневой опасности на изучаемой территории: литология (а), расстояние до разлома (б)

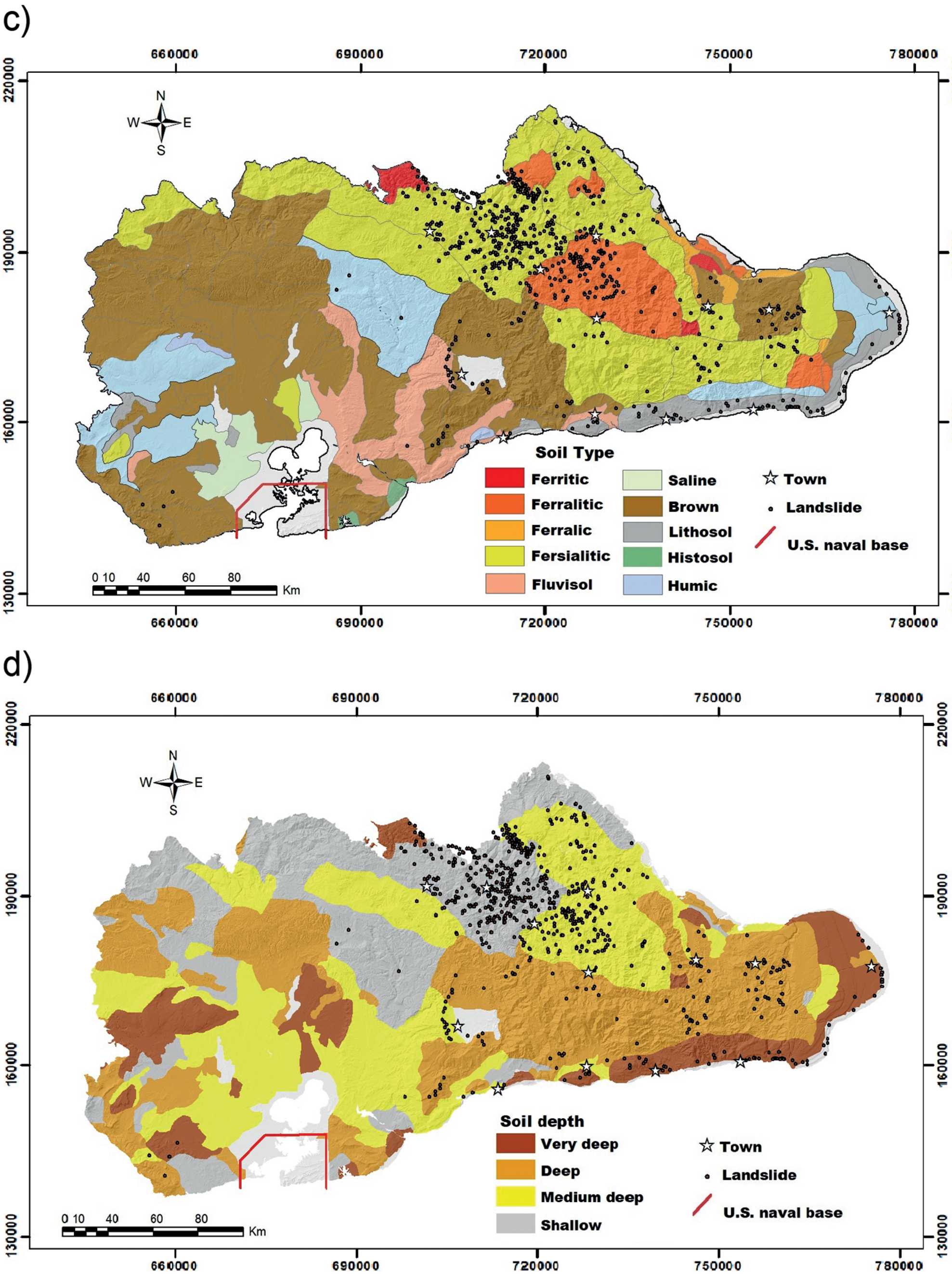

Fig. 4. Maps of conditioning factors that make the study area susceptible to the occurrence of landslides: Soil type (c), Soil depth (d)

Рис. 4. Карты обуславливающих факторов оползневой опасности на изучаемой территории: тип почвы (c), мощность почвы (d)

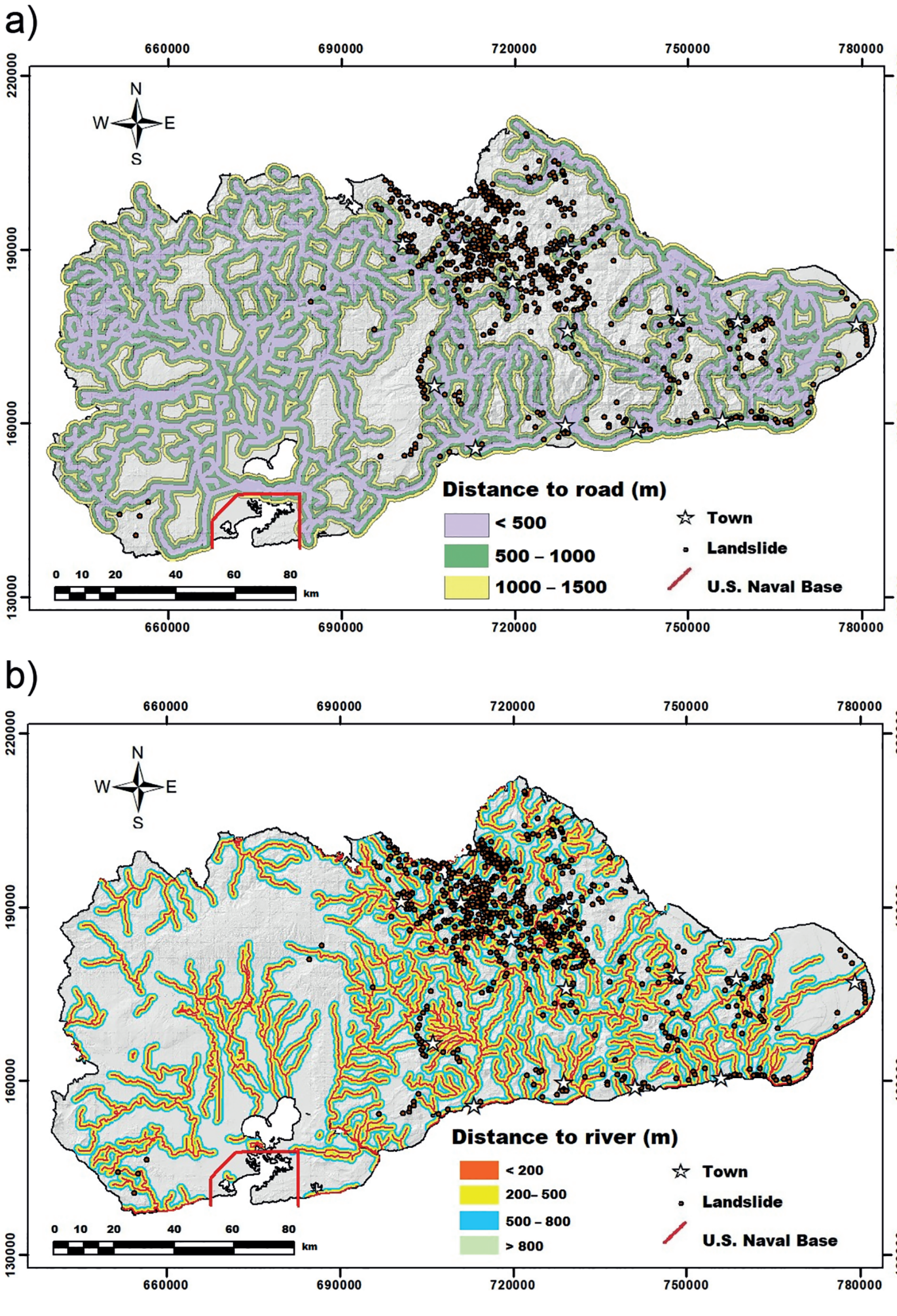

Fig. 5. Map of conditioning and triggering factors: Distance to road (a), Distance to river (b),

Рис. 5. Карты обуславливающих и инициирующих факторов: расстояние до дорог (а), расстояние до рек (б)

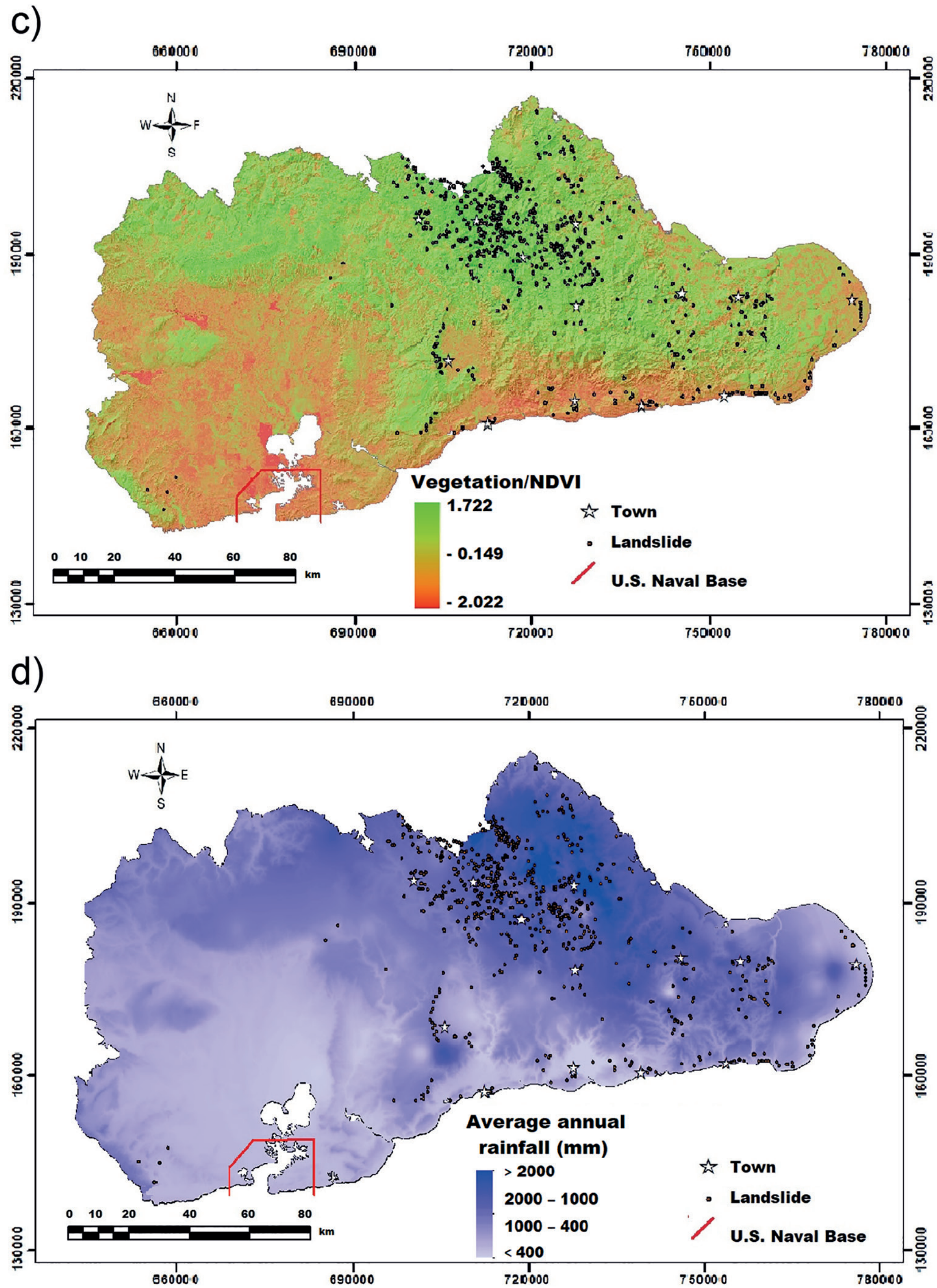

Fig. 5. Map of conditioning and triggering factors: Vegetation/NDVI (c), Rainfall (d)

Рис. 5. Карты обуславливающих и инициирующих факторов: нормализованный относительный индекс растительности/NDVI (c), среднегодовое количество осадков (d) tion in all class ranges, with the range of «low depth» and «medium depth» being the ones with the highest incidence of landslides. This corroborates what was expressed by Pospehov [42] that generally shallows landslides occur in the area.

Anthropogenic factors are defined as the factors caused by human activity such as mining [50—53], vegetation removal, etc [54, 55]. The distance to the road is a very important anthropogenic factor in the occurrence of landslides [56—59]. An analysis of proximity to the road network was carried out and it was reclassified into three classes as shown in Fig. 5, *a*. The hydrological network in the study area is extensive. For reclassification, distances to rivers of: (i) < 200 m, (ii) between 200 and 500 m, (iii) between 500 and 800 m and (iv) > 800 m for a significance for instability of very high, high, medium and low respectively (Fig. 5 *b* and Table 3).

Rainfall is a triggering factor, which in the region turns out to be the most important [60, 61]. These findings confirm the relationship between the occurrence of landslides with intense rainfall found by other authors [62—66]. The rainfall was reclassified into four classes as shown in Table 3. It was found that many of the inventoried landslides coincide with the classes with the highest accumulated rainfall (Fig. 5, *d*).

Landslide susceptibility evaluation

The results of the AHP comparison matrix in Table 4 show that the maximum weighting of the factors is accumulated by the average annual precipitation, slope angle, elevation and distance to fault with 0.19, 0.15, 0.14 and 0.11 respectively, followed by the weights, distance to river (0.09), distance to the road (0.08) and lithology (0.08), while factors such as vegetation/NDVI, have little incidence.

After computing the *LSI* values for the area, four susceptibility zones were defined: null susceptibility, low, moderate and high. Based on this classification, a landslide risk zoning map of the study area was prepared (Fig. 6). The landslide susceptibility map shows that the northeast area of the province is most affected by land-

Table 4

Pair-wise comparison of conditioning factor layers and weight
Попарное сравнение уровней и веса обуславливающих факторов

Factor	Slope angle	Elevation	Distance to fault	Distance to river	Distance to road	Soil depth	Soil type	Lithology	Vegetation/ NDVI	Average annual rainfall	Weight	Consistency Ratio (CR)
Slope angle	1.00										0.15	0.0667
Elevation	1/2	1.00									0.14	
Distance to fault	1/2	1/2	1.00								0.11	
Distance to river	1/3	1/2	1/2	1.00							0.09	
Distance to road	1/2	1/3	1/2	1	1.00						0.08	
Soil depth	1/3	1/4	1/2	0	0	1.00					0.07	
Soil type	1/2	1/3	1/3	1	0	1/2	1.00				0.07	
Lithology	1/3	2	2	2	2	1/2	1/6	1.00			0.08	
Vegetation/NDVI	1/6	1/5	1/6	1/6	1/8	1/7	1/6	1/2	1.00		0.02	
Average annual rainfall	2	2	3	2	3	2	3	2	3	1.00	0.19	

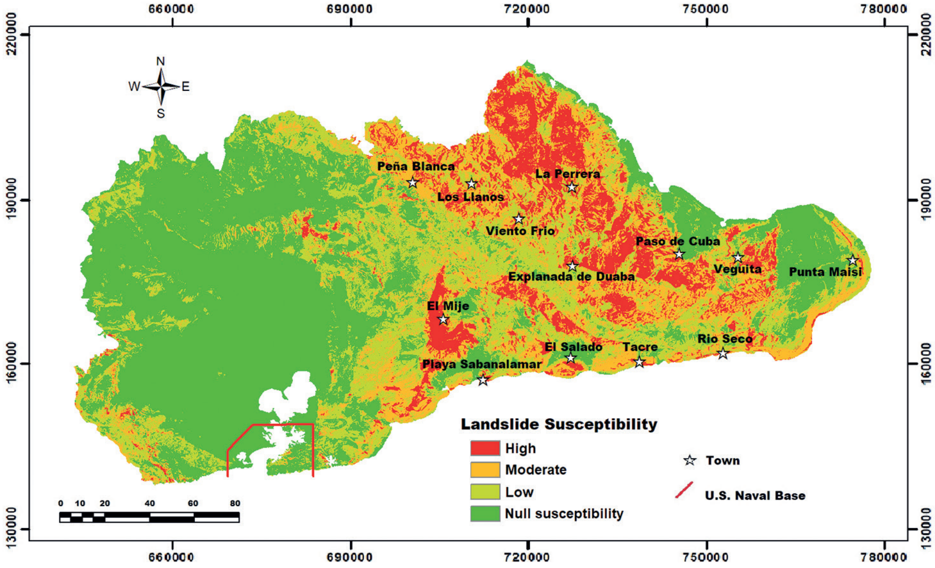

Fig. 6. Landslide susceptibility map of the Guantanamo province
Рис. 6. Карта зон оползневой опасности провинции Гуантанамо

slides. They coincide with a high proximity to faults and bodies of water. This zone is also constituted fundamentally by rocks of the metamorphic and ophiolitic complexes, mainly composed of schists and rocks of an ancient oceanic crust with hazburgites, lherzolites, and serpentinized dunites, respectively. The southern zone presents in its generality moderate susceptibility; It should be noted that precipitation is a triggering factor that influenced this result, since in this area the average annual precipitation values are the lowest in the country. Low susceptibility zones are generally found in the western parts of the study area, coinciding with the Guantánamo Valley, which presents very low elevation values.

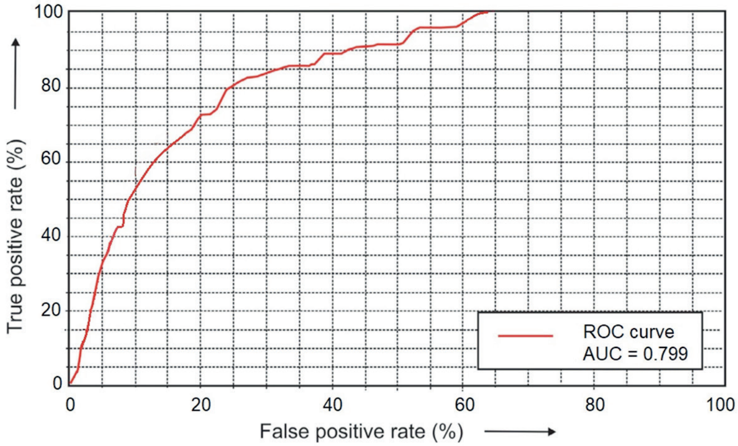

Fig. 7. ROC plot used for the validation of LSZ map
Рис. 7. График ROC для проверки карты

The validation of the landslide susceptibility zonation (LSZ) map was carried out with the help of data from previous landslide inventories in the study area. It is assumed that if past landslides in the study area develop within very high or high susceptibility zones on the prepared LSZ map, the prediction model is quite reasonable [67]. The Receiver Operating Characteristics (ROC) method was used. The ROC method is quite applicable and is mainly used for validation of susceptibility maps [45]. The analysis is performed with the help of a graph representing the rate of true positives (Y-axis). If the data between the inventory used and the prediction model built represent a coincidence, it represents a false positive; the lack of coincidences will represent false positives (X axis) [68]. The study presented a high coincidence between the areas with high and moderate susceptibility values and the occurrence of landslides because the curve tends to true positive values (Fig. 7).

Conclusions

Landslides are complex exogenous processes and require systematic monitoring and the creation of predictive models to analyze and delineate susceptible zones in an area to these phenomena. Landslide susceptibility zonation was carried out through multiple criteria decision analysis. For this purpose, ten factors that affect the occurrence of landslides in the study area were considered; they were assigned the appropriate weight following the Analytical Hierarchy Process (AHP). The factors with the highest weights were mean annual precipitation, followed by slope angle, elevation, and distance to fault. The vegetation factor is the one with the lowest weighting value. The northeastern parts of the study area are found in zones with high and moderate susceptibility. They coincide with a high proximity to faults and bodies of water. This zone is also constituted fundamentally by rocks of the metamorphic and ophiolitic complexes, in their generality very structurally affected. These complexes are mainly composed of schists and rocks of an ancient oceanic crust with hazburgites, lherzolites, and serpentine dunites, respectively. The southern zone presents in its generality moderate susceptibility; being the average annual precipitation factor the one with the greatest influence, because this area presents the lowest values in the country. Low susceptibility zones are generally found in the western parts of the study area, coinciding with the Guantánamo Valley, which presents very low elevation values. Using the weights for the factors considered and the appropriate ratings for the classes of factors, the landslide susceptibility index was developed to prepare the landslide susceptibility zoning map. The map was validated with the help of the Receiver Operating Characteristics (ROC) method. It was found that the calculated area under the curve (AUC) is 0.799, which reasonably validates the landslide susceptibility map of Guantanamo province.

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Authors confirm that data provided in this research is available at the Meteorological Center in Guantánamo, the Mountain Development Center, the Soil Institute and the Geology and Paleontology Institute of Cuba.

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