Vol. 63, No. 3 – Summer 2020

News

SPECIAL FEATURE

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Risk Susceptibility Mapping Based on the Urban Geology of the City of La Paz, B.C.S., Mexico

(NE-SE portion)

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Abstract

Geology, as a tool to identify areas of geological risk, is useful for examining the close relationship between a city's geological environment and its sustainable development. By understanding this relationship, one can respond to the growing demand for solutions to both environmental and urban problems. In the study area, the need to create new urban areas is growing at the national, regional, and local levels. However, urban development has not been linked to an adequate analysis of the geological environment and an understanding of the main factors that control risk conditions. Consequently, the risks and their impacts have manifested themselves due to several factors. The methodology to achieve the objectives was based on a characterization of the geological, hydrogeological, and geomechanical conditions of one of the main urban settlements of the city of La Paz, capital of the state of Baja California Sur, Mexico, and generation of a set of thematic maps using the Analytic Hierarchy Process (AHP) methodology, and finally a risk susceptibility map for flood events, debris flows, rock falls, and landslides. The results represent the first phase of a larger-scale project to develop new information supporting a more detailed zoning of geographic risks, which will provide for the sustainable growth of the population of the state capital, the improvement of current construction standards, and the corresponding zoning to provide for the city's orderly development. Finally, it is thought that this type of risk susceptibility mapping (urban settlement scale) provides an analysis of the risk conditions, which any city citizen can use to find their location and understand their level of civil protection, as opposed to most risk studies that offer broad-scale results and only offer a general view.

Key words: Geological risks, sustainable urban development, RS (Remote Sensors), GIS (Geographic Information Systems).

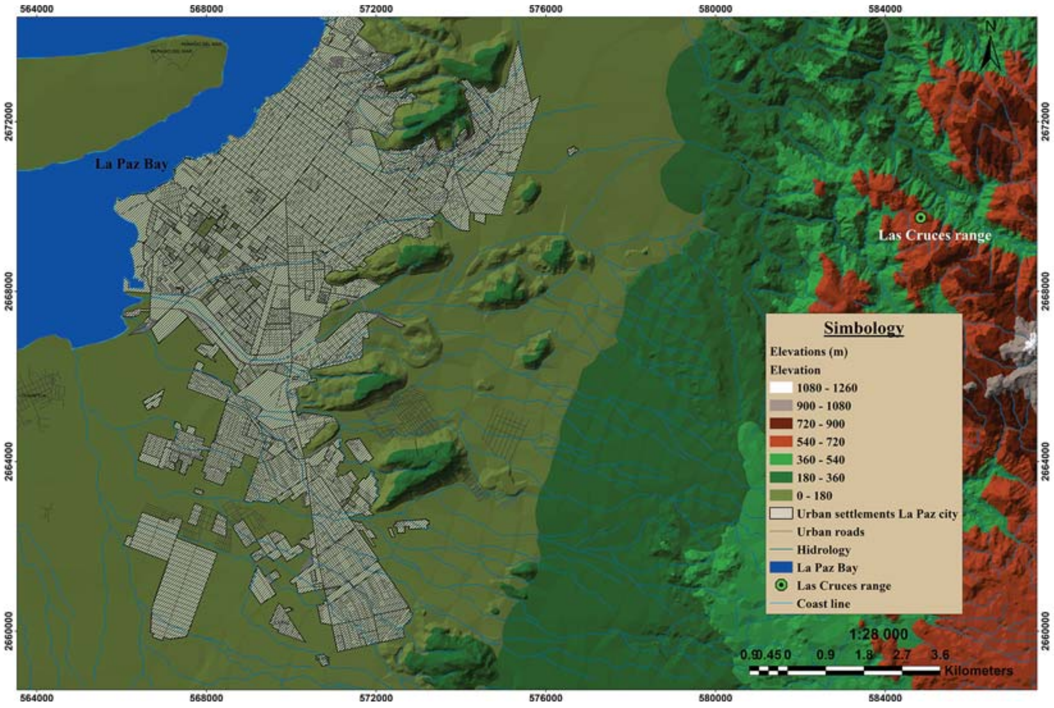

Figure 1. *General location map of the study area*

1. Introduction.

The natural hazards that occur on our planet are always linked to the Earth's geodynamics, which include geological and hydrogeological processes. Therefore, it is very important to understand and apply the knowledge we have of the Earth's geodynamics in order to prevent and mitigate their effects. Geology and its environment make up the geological environment with which human beings constantly interact. This interaction is in a constant dynamic and evolution, which leads to processes that affect both the natural and human environment. The former is shaped by geology, biology, and edaphology, and the latter is the anthropic, represented by cities, infrastructure, public works, populations, etc. Both environments interact constantly, and in the case of the study area, a planned and sustainable relationship that allows a harmonious relationship between the two has not yet been established. The search for this "empathy" between the environment and the human being has come to shape disciplines such as Urban Geology, which, in recent years, has gained relevance in Mexico, and is becoming a new and important urban development planning tool. The concepts of hazard, vulnerability, and geological risk can help to evaluate the tight-knit relationship between changes in the geological environment and urban development [1-2].

Most of Mexico rests on the southwest corner of the North American plate, which is bordered by the Pacific plate carrying the Baja California peninsula, and the Rivera, Orozco, Cocos and Caribbean plates. Mexico is located along the Ring of Fire, where tectonic activity is high, and which accounts for 80 percent of worldwide seismic and volcanic activity. In addition, the country is located within four of the six cyclone generating regions in the world, which influence the territory of Tehuantepec, the Eastern Caribbean Sea Region, the Campeche maritime platform, and the Eastern Atlantic Region. In total, this geo-climatological location encompasses 17 Mexican states, containing almost half the Mexican population, in areas of vulnerability and risk [3]. Therefore, the geological, hydrogeological, and meteorological conditions of the environment encompassing the city of La Paz, Baja California Sur, Mexico, are determining factors in its urban geology, since these elements play an important role in potential risks (floods and landslides) in the city's urban and suburban areas.

In the study area, the need to create new urban areas is growing at the national, regional, and local levels. However, urban development is not linked to an adequate analysis of the geological environment and an understanding of the main factors that control risk conditions. Consequently, the adverse impacts of urbanization manifest themselves due to various factors, such as: (1) global climate change, (2) inadequate land use planning, (3) ignorance of the geological environment, and (4) uncontrolled urban-population growth. This disconnect is reflected in several natural disasters that have occurred in various Mexican population centers. Examples include the population centers of Minatitlán, Jalisco [4, 5], Meztitlán, Hidalgo. [6], Chapala, Jalisco [7], and Totomoxtla, Puebla [8], where floods and landslides have wreaked serious damage.

The purpose of this research is the continuation of the assessment of geological hazards at the local level in the southeast part of the city. This assessment will focus on the interaction between the geological environment and the urban environment. Study of the geologic risk factors will increase the understanding of the pre-development conditions in the southeastern portion of the city of La Paz. Thus, the need becomes apparent for an update of the understanding of the geological-urban environment that supports the state capital's sustainable urban-population growth, improvement of current construction regulations, and the corresponding mapping to plan for the city's development in an orderly manner.

2. Study Zone

La Paz, capital of the State of Baja California Sur, is located in the southern part of the peninsula of Baja California, Mexico. The predominant hydrogeological conditions of the southern region of the Baja California peninsula are classified as arid to semi-arid (average temperature of 30.37 ° C) [9, 10], which leads to a high incidence probability for tropical storms and hurricanes that develop in the Eastern Pacific. Over the last decades, the average annual rainfall is 164.59 mm.

The city of La Paz is characterized by a topography dominated by basins and mountains, which are the result of the interaction of magmatic and tectonic processes. Holocene alluvial material consisting of sand to sandy gravel fills the modern streams in deposits of varying thickness and reaching a few meters thick in the main streams [11]. Geologically, sedimentary and volcanic rocks (sandstone and volcanic conglomerates, rhyolitic tuffs, andesitic lahars and lava flows) are mapped as the Comondú Formation, with an age between 30 and 12 Ma in the central portion [12–16]. Structurally, the valley of La Paz is formed by a graben with north-south orientation, bounded on the east by the La Paz Fault on the slopes of the Las Cruces mountain range, and on the west by the El Carrizal Fault [17]. The geological-structural conditions place the study area in a setting with permanent micro-seismicity. The total population of the city of La Paz is 251,871 inhabitants [18]. The study area has a size of 85.96 km^2 and is located in the southeast portion of the city of La Paz, located between coordinates UTM 12 R 569000-575000 E and 2664000-2674000N (Figure 1).

3. Methodology

The risk mapping consists of the delineation and characterization of a space and / or area of the physical environment according to certain properties and constitutes one of the pillars of urban planning. The complexity of these interrelationships makes it difficult to estimate hazards in an integrated manner, so viewing the hazards individually is considered to be more appropriate with respect to the sustainability scheme that is to be factored into the planning of the territory and particularly into the risk mapping. Thus, an adequate mapping of risks must encompass the study of the specific risks that, due to the action of each of the identified natural hazards, occur in an area. By this methodology and with the support of several tools and guide classifications [19–20], it is possible to characterize risk conditions (including their dimensions) (Figure2).

The Analytic Hierarchy Process (AHP) method used in this paper is a mathematical method created to evaluate alterna-

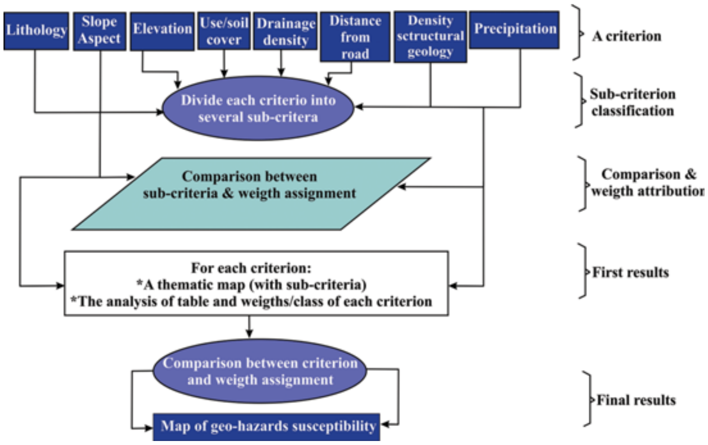

Figure 2. *Methodology applied to the study area*

tives when several criteria are considered. The method is based on the principle that the importance and understanding of the factors are as important as the data used in the process. The AHP developed by Saaty (1980) [21] consists of matrix analysis and involves value judgments. By this method, a hierarchical matrix of the selected criteria was established, which generated the weighting of the eight selected variables. It was based on the understanding of the study area, the documentation and local studies generated to date, and the criteria of the specialists.

Table 1. Values assigned to the conditioning factors for areas susceptible to geo-hazards

No	Factor	Class	No.	Weight (wi)	Index	Observations
1	**Lithography**	Aluvium	1	20	20	The lithology with the greatest susceptibility to slip is the rhyodacite due to its high degree of fracturing and accumulation of rock masses.
		Sandstone	2		40	
		Tuff	3		60	
		Conglomerate	4		80	
		Rhyodacite	5		100	
2	**Slope**	0.0–10.8	1	16	16	The highest percentage of the slope is concentrated in moderately inclined (25 ° -28 °) to inclined. The slope aspects of north, northeast, and northwest are located in the high parts of the relief where the areas of depletion and fallen rocks are located.
		10.8–21.6	2		32	
		21.6–32.4	3		48	
		32.4–43.2	4		64	
		>43.2	5		80	
3	**Elevation(m)**	0.0 –76	1	15	15	The highest elevation is located NE of the city increasing the possibility of landslides, rock fall and floodplain.
		77–153	2		30	
		154–229	3		45	
		230–306	4		60	
		307–382	5		75	
4	**Use/Soil Cover**	Urban settlements	3	14	14	The use of soils is dominated by its use in housing, with surrounding areas of soil and endemic vegetation.
		Urban zone	2		28	
		Forest soil	1		42	
5	**Drainage density(m)**	0.0–59.7	1	12	12	Drainage flows through the urban center of the study area, which increases its risk influence.
		59.7–119.4	2		24	
		119.4–179.2	3		36	
		179.2–238.9	4		48	
		238.9–298	5		60	
6	**Density of urban roads(m)**	0–5.6	1	10	10	Landslides in forms of depletion and/or falling rocks do not occur near the communication routes.
		5.6–11.2	2		20	
		11.2–16.8	3		30	
		16.8–22.4	4		40	
		22.4–28	5		50	
7	**Density of Structural features $(No./m^2)$**	0.0–6	1	8	8	Fractures, stratigraphy and foliation planes are a factor to consider in the vicinity of inhabited areas.
		6–8	2		16	
		8–9	3		24	
		9–21	4		32	
		21–25	5		40	
8	**Rainfall**	<100	1	5	5	The average annual rainfall for the El Cajoncito basin, where the area is located, is 200mm/year. The climatological station near the study area provides rainfall data over a period of decades.
		>100	2		10	

3.1. Estimation and Numerical Assignment of Slip Factors.

The determination of the numerical allocation of the landslide risk assessment factor is a numerical system that depends on the relevant factors. By superimposing the elements or parameters that indicate geological and hydrological hazards, a zoning map of susceptibility can be developed, as well as a delineation of the possible risk areas, granting each factor a specific weight and value, and analyzing the situations site by site, with the help of the various thematic maps [22].

The AHP uses comparisons between pairs of elements, building matrices from these comparisons, and using elements of matrix algebra to establish priorities among the elements of a level, with respect to an element of the immediately higher level.

In the study area, specific factors of the physical environment were identified and numerical values were assigned to the factors according to the degree of influence. The different classes within each causal factor were also assigned values according to their influence, to give a more precise assignment of each causal factor and their respective subclasses.

Relevant factors for the zoning mapping of susceptibility to landslide risks include lithology, slope, elevation, land use and land cover, urban road density, line density, drainage density, and precipitation. The maximum numerical estimate of the sliding risk evolution factor for different categories is determined based on their estimated probability to cause instability. The important factors responsible for the geo-hazards (landslide & floods) area were assigned numerical values (range) on a scale of 1 to 5 in order of significance (Table 1).

This part of the methodology is the basis for giving weight (wi) to each parameter and defining its relative probability to induce landslides (Ri). These weighted factor maps were superimposed using a multivariate criteria analysis to prepare a risk susceptibility map (MSR) for the study area [23].

3.2. Mapping Risk Vulnerability

The risk vulnerability map is based on a zoning of landslide risk (rockslide, debris flow, and rockfall), which was prepared when calculating the landslide potential index and classifying the slip potential index in several lands susceptible to landslide, as low, medium, high and very high.

The slip potential index (SPI) is defined as:

$$SPI = \Sigma n\ i = 1\ (wi * Ri)\ (1)$$

Where wi denotes the weight for the factor i and Ri denotes the classification of the class of the factor i. In this study, the total number of factors (n) is 8, where the class classification varies from 1 to 5. The landslide model was created and the weighting and classification are assigned to each category. Depending on the issues and their impacts, different areas were delineated.

The total estimated zoning of landslide risk (ZLR) was calculated as follows:

$$Value\ ZLR = L + SL + ELE + SL/U\text{-}SL + DD + URD + SFD + RF$$

Where, *Value of ZLR = Sum of ratings of all the causative factors, ZLR = Lithology + Slope+ Elevation + Soil/Use Soil + Drainage Density+ Urban Road Density + Structural Density + Rainfall*.

The different thematic layers were reclassified using the Jenks method, which is based on Jenks natural break algorithm, thereby minimizing the internal variability of the classes and maximizing the differences between classes. In addition, the Latent Semantic Indexing (LSI) was used to prepare the risk susceptibility map (RSM), whereby all the layers of the map were superimposed and validated using the landslide incidence points collected during fieldwork.

Based on this methodology and through the use of the ArcGIS software, several thematic maps based on and related to the digital elevation model (DEM) were generated: general geological map, elevations, slope, aspect, drainage, land/vegetation use, precipitation, and as a final product, a susceptibility map.

4. Results and Conclusions

The methodology employed by this research work resulted in the generation of vulnerability (susceptibility) maps for geological risks that for the first time are focused on different geological issues of the urban and suburban area, and that can be used as a basis for the future sustainable urban development of the city of La Paz. These areas include urban development zones where streams are located and that are susceptible to flooding, as well as hill slopes having characteristics susceptible to landslides. This research work also highlights the methodology used, the possibility of evaluating susceptibility conditions at the state and regional level, and the employment of statistical methods to complement the work, as has been done by other authors [24–29].

Due to its climate, topography, type of soils and slopes, the Valley of the City of La Paz, BCS, Mexico, has a surface hydrology characterized by runoffs that drain through small channels (streams) to the Bay of La Paz. Low velocity runoff generates significant areas of flooding in the suburban areas of the NE-SE portion, which extend and cross, sometimes causing severe damage to the population (Figure 3).

The urban geology of the study area is characterized by an isolated sequence of rocks outcropping in its southwest portion, which consist chiefly of volcanic and volcano-sedimentary rocks. These rocks are mapped within the Comondú Formation, which is known within the area for its geomechanical condition and anthropic action. In an appendix, families of structural data were analyzed, and it was possible to distinguish a series of alignments and irregularities in the drainage pattern corresponding to a series of failures with a normal component that cuts off the top of the lithological sequence and which have a length of about 10 meters with dominant course as possible failures or fracture.

One fault and three main joint orientations were recognized (Faults N10°E/28°SE, Fracture 1: N20°W/50°SW, Fracture 2: S 45°E/85°NE and Fracture 3: S70°E/85°SE). Discontinuity data were represented on stereographic diagrams and kinematic maps to identify the areas of greatest susceptibility.

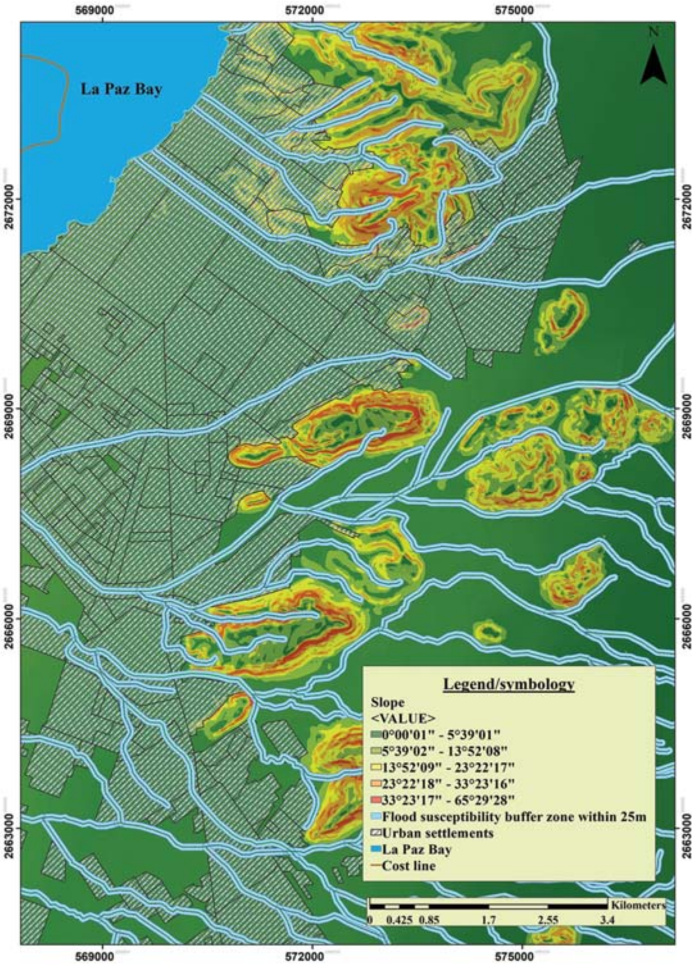

Figure 3. *Map showing the spatial-vectoral analysis of hillslope aspect, stream conditions and buffers, and areas vulnerable to flooding*

The lithological conditions and their characterization are related to other factors (hydrogeological, hydro meteorological, and geomechanical) that generate the movements of removal of masses and blocks of rock.

Based on the above conditions, fall processes, landslides and/or rock flows were recognized. Of these two sets, only 6 debris flows and 35 rockfalls (within high-temperature volcanic clastic deposits), in the upper and middle parts of the topography, without soil identification in these processes were identified in the area. Both occur in events mainly in falling movements, such as simple translational and block sliding that end up as slow movement flows according to the classification of Dikau et al. (1996) [30]. The failure mechanism and detachment mode are controlled by geological and geotechnical factors. The volumes of rocky material removed in each removal process range from the order of meters to hundreds of cubic meters, and the individual blocks weigh from 5 to 50 tons.

The movements were generated by a combination of geological factors (slope, lithology and geological structure), hydrogeological (drainage density), and geotechnical (mechanical behavior of materials). The mechanism of failure and mode of detachment were controlled by geological and geotechnical factors.

Figure 4. *(A, B, C, D, E) Panoramic showing areas susceptible to flood*

xThis aspect of the results coincides with the research carried out by Momeni (2016), [31] Ahmed (2014), [32] when affirming that in landslides and fallen rocks, slope and aspect play an elementary role in the flow of material since the slope provides speed and aspect indicates the direction of that slope.

These phenomena coincide in the location of urban settlements of this type that are established at the foot of the existing topography. Therefore, it is considered useful to carry out more in-depth studies on the aspects that generate these landslide processes.

The distribution of these events was located within the slopes (27° to 40°), which is limited by the main streams: El Cajoncito and Los Bledales. The streams cross the northeast and southeast portion of the city of La Paz and in turn coincide with some important urban settlements (San Pablo Guelatao, La Escondida, Lazaro Cardenas, Francisco Villa, 20 de Noviembre, Roma, Flores Magon, Costa Azul, La Rinconada, Agua Escondida, El Cardonal) since they are established along the margins of the hills and streams (Figure 4). This geohydrology and hydrometeorological condition denotes the poor urban planning and the high risk for its population, being settled in areas susceptible to flooding and landslides (debris flow and rockfalls).

The results obtained based on this geotechnical characterization (Geological Strength Index (GSI)) turn out to be very homogeneous and close in parameters, since it is a volcanic and vulcanosedimentary lithology with a similar genesis in processes and evolution time. The geomechanical behavior of the lithology is based on the observations at the outcrops level where the structure of the lithology formed by well-defined rock segments in two to three directions is appreciated, which constitutes normal failure and fractures in joints (Figure 5). The conditions of the discontinuities are very good to good (range 70 to 80) since the surfaces are weather-resistant (Figure 6) [33].

The processes of removal of rock masses and blocks of rocks are confined to the upper and middle part of the topography (100 to 50 meters above sea level) with 90% of events represented by only a single lithology: Rhyodacite. These events are basically simple block and/or translational landslides, which has a high influence by the factors of structural geology, erosion and gravity as sliding mechanisms.

The current research presented a methodological model for the evaluation and zoning of the susceptibility of geo-risks according to the characteristics of the study area.

It also highlights the proposed methodology, the possibility of evaluating the conditions of susceptibility at the state and regional level, complementing this work with statistical methods and the generation of an inventory of landslides (mass and fallen movements), which will allow comparing their results and coherence in the distribution of the occurrence of all present and future landslides, rockfalls or any geological risk.

In addition, the percentage and geographical distribution of risk susceptibility in this Northeast and Southeast portion of the city is clearly observed (Figure 6–7).

The methodological proposal also complements the results obtained with a new map of susceptibility of geological risks (Figure 7), which did not exist until today and that allows defining urban areas of urban development susceptible to these phenomena at urban settlement scale (1: 50,000).

Acknowledgments

The author thanks the Technological Institute of La Paz for the logistical support provided.

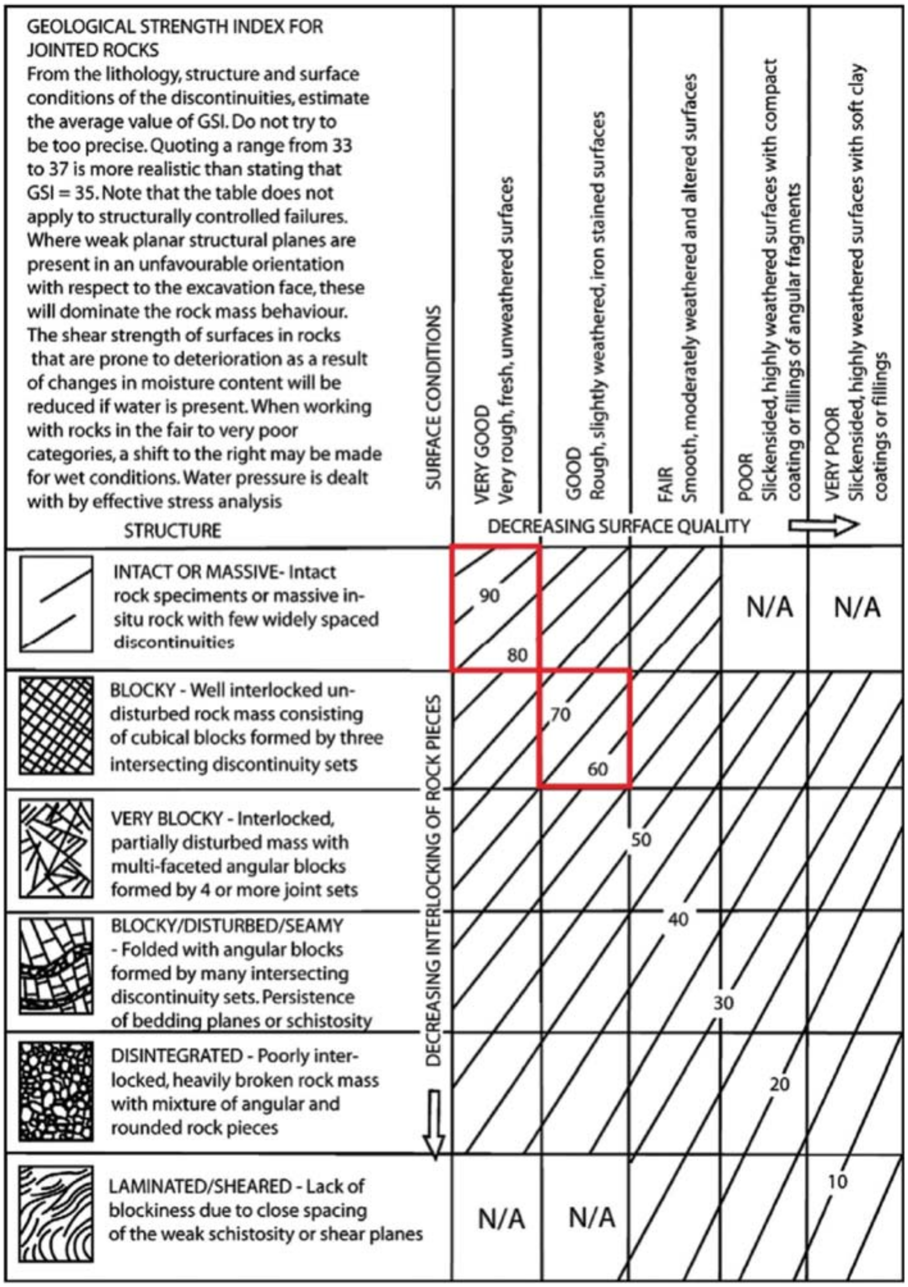

Figure 5. *Estimation of the Geological Strength Index, GSI, based on a Geological Description of the Rock Mass (Marinos & Hoek, 2000)*

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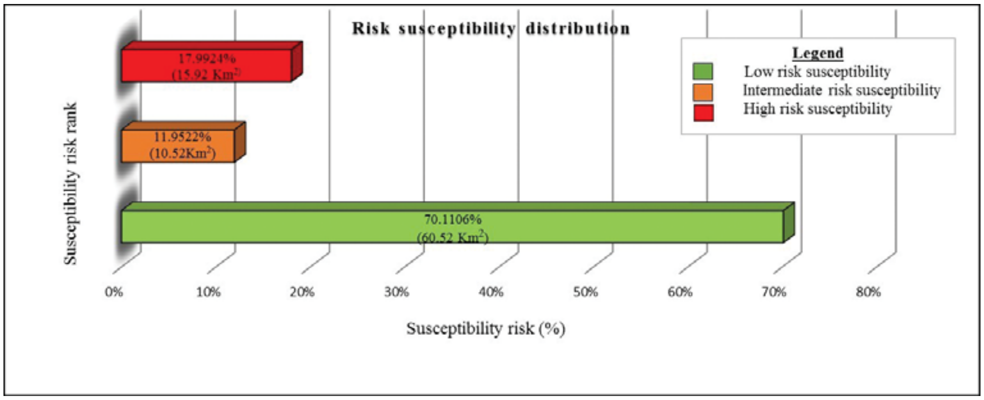

Figure 6. Table showing the distribution of risk susceptibility

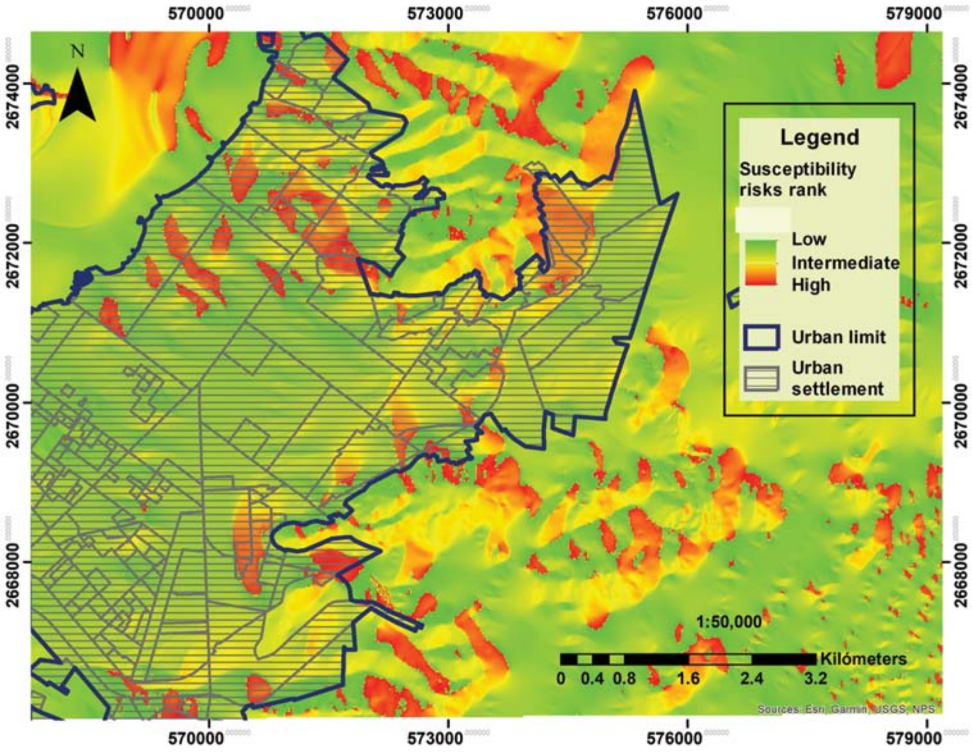

Figure 7. Map showing the vulnerability by urban settlement in the northeast-southeast area

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