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Research Article

Susceptibility Analysis of Geo-Hazards of the City of La Paz, Baja California Sur, Mexico, Case Study: Urban Settlement Marquez De León

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ABSTRACT

Geology as a tool to identify areas of geological risk is useful to determine the close relationship between the geological space and the sustainable urban development of a city. From this interaction, you can respond to the growing demand for solutions of an environmental and urban nature. At the national, regional and local level where the study area is located, there is a growing need to create new urban areas, but these are not linked to an adequate analysis of the geological environment and the knowledge of the main factors that control risk conditions and consequently, its impacts have manifested due to different 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 urban settlements of the city of La Paz, capital of the state of Baja California Sur., Mexico and with it, a set of thematic maps using the Analytic Hierarchy Process (AHP) methodology and finally a risk susceptibility map related in local areas to flood events, debris flows, rock falls and landslides. The results represent a first stage of a larger-scale project and with this it is possible to contribute new knowledge to be used in the most precise zoning of geo-hazards, which will allow the state capital a sustainable growth of the population of the city, the improvement of the current construction standards and the corresponding zoning to anticipate its development in an orderly manner.

Keywords

Geological risks; Sustainable urban development; Zoning; Analytic Hierarchy Process (AHP)

INTRODUCTION

The geological and hydro meteorological risks are currently responsible for high rates of damage and destruction to urban areas, in the twentieth century alone it is estimated that more than one million people worldwide have died as a result of earthquakes. In Latin America, these earth movements are constant and bring landslides and rocks as a side effect. The environmental interactions between factors such as climate, topography, geology and mechanical resistance of the rock (Geological Resistance Index-IGR) [1] play a very important role as triggering mechanisms for removal processes; In order to increase knowledge of these types of processes, it is necessary to consider these relationships in the removal processes.

In Mexico annually, more than 50% of the disasters that occur in the country are triggered by phenomena of hydro-meteorological origin, hurricanes and other types of torrential rains stand out, floods, droughts, frosts and hailstorms, among others [2], being Baja California Sur the entity with an average cyclone incidence of a tropical cyclone in the Northeast Pacific and 2 approach less than 300 km. Between 1966 and 2010, 39 cyclones have arrived at the entity, 20 of which have arrived in September [3]. In addition, considering that the volume of runoff (11 Mm3 / year, product of a precipitated volume of 351 Mm3 / year) by the streams that make up the La Paz Basin extend and cross the urban area with low speeds [4]. It is considered that the geological characteristics of the Southern Region of the Baja California Peninsula where the city of La Paz is located have been described in several research papers by various authors and institutions at the level of regional and local geology, [5-9], and more recently the work done by Pérez-Venzor, 2013 makes a geological-geochemical study of the southern portion of the State (Los Cabos Block) where it refers to this study area as part of a Geological Province Plutonic Complex of La Paz.

All the previous antecedents are focused on different geological knowledge objectives, but there is little regional and local research that includes urban geology aimed at geological engineering and geotechnical purposes, this material being little known; such as in Guaymas, Sonora [10] where he characterized the area based

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on local geology in several aspects and developed several thematic maps; on the other hand in the city of Tijuana Baja California, it was performeda diagnosis of urban risks [11] where a geological characterization of the city was made. Within Baja California Sur, urban geology has focused on isolated works that consist of the identification of geological hazard zones in the southern portion, in the area of Cabo San Lucas [12] and recently in 2012, the natural risk atlas was developed at the state level. Therefore, it is observed that a more timely geological recognition is required, this is on a scale (urban colony) where the possible geological risks and the risks derived from geological and hydrometeorological events are characterized and identified.

Study zone

La Paz, capital city of the state of Baja California Sur and in turn head of the municipality of La Paz, which is located in the southern portion of the Peninsula of Baja California, Mexico; Within the Köppen classification, the dominant climates are very dry and very warm, with an average annual temperature ranging between 22 ° C and 24 ° C, with rains in summer and winter mainly, where winter precipitation is 10.2%. with great influence of atmospheric disturbances originated in the Pacific Ocean of cyclonic type, which produce very intense rainfall. The city of La Paz is characterized by a morphology dominated by basins and mountains, the result of the interaction of magmatic-tectonic processes, which is based on Holocene deposits that correspond to alluvial material (varying from sand to sandy gravel) of active streams, where the thickness of the material varies and can reach a few meters in the main streams. Geologically in the area, volcanic and volcanoclastic rocks (sandstones and volcanoclastic conglomerates, rhyolitic tuffs, andesitic lahars and lava flows) are represented by the Comondú Formation with an age between 30 and 12 Ma in the central portion [6,8,13]. The total population of the city of La Paz is 251,871 inhabitants, of which 126,397 are men and 125,474 are women. The area under study within this state capital is Marquez de León urban settlement, which is located in the northwestern portion of the city of La Paz, with a latitude of 24° 8´51´´ N and a longitude of 110° 16´10´´ W [Figure 1]. In addition, it has an area of 487,000 square meters.

Geology of the marquez de León urban settlement

Lithology

The lithology is represented in a volcanic and volcano sedimentary sequence, distributed in isolated outcrops within the area [Figures 2 and 3]. Therefore, it is necessary to mention that there are no outcrops with stratigraphic continuity, or rock body, which can serve as an index horizon that suggests the position that a given unit occupies in the sequence, with the exception of the "Riodacita Providencia" [14]. For example, the movement of lava or pyroclastic spills controlled by the contemporary drainage pattern to volcanism, combined with erosion effects.

Structural geology

In the regional area that includes the Marquez de León urban settlement, it is possible to distinguish a series of alignments and irregularities in the drainage pattern and slope of the relief in the NS direction that are controlled by normal component faults, which have a scale of about 10 m. long with a dominant heading NE or fractures in the form of diaclases that form patterns [Figure 4]. It is considered that in this region there may be a normal inclined fault towards which the base of the riodacitic spill emerges at heights greater than 200 m as in the Atravesado Hill, but that it is difficult to give continuity since there are many deposits of debris that cover the lower parts of the topography [Figure 2]. In an annexed way, families of structural data were analyzed where it was possible to distinguish a series of alignments and irregularities in the drainage pattern, a series of failures with a normal component that cuts the upper part of the lithological sequence were recognized. Which have a scale of about 10 m. of length with dominant course as

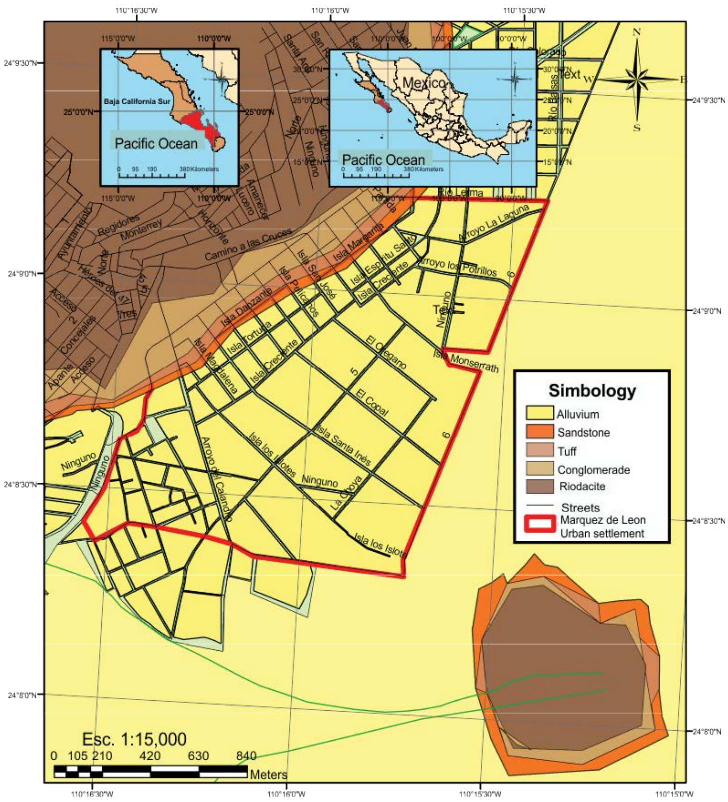


Figure 1: Geology of the Marquez de León colony located in the northwestern portion of the city of La Paz, Mexico.

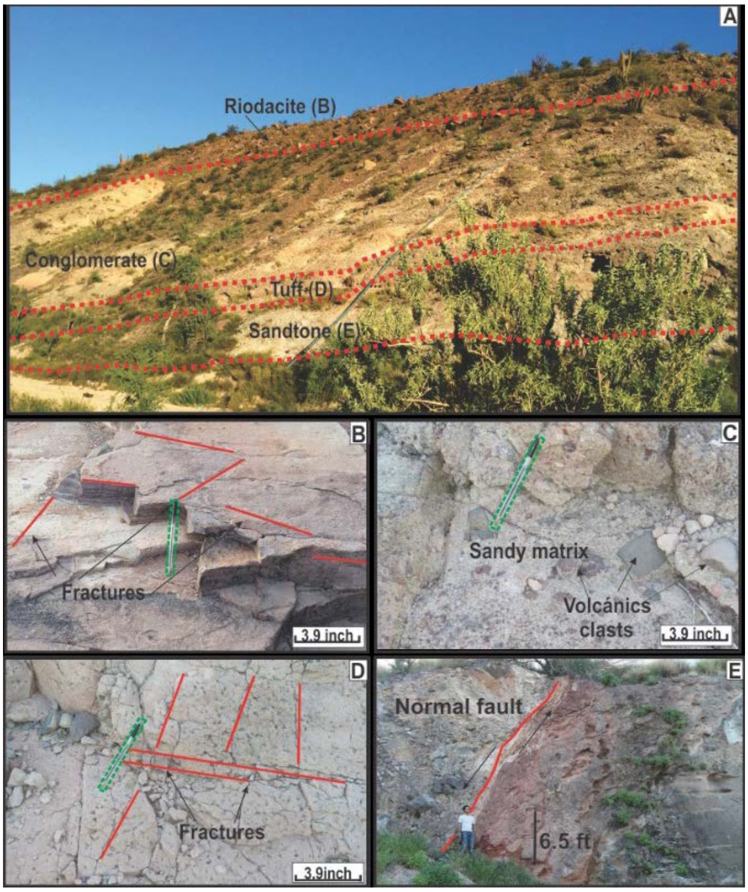


Figure 2: Dominant lithology in the study area. A) Outcrop showing the dominant rocks of the study area, with some structural features and their granulometric composition. B) Riodacite, rock that crowns the entire sequence C) Conglomerate forms the most powerful stratum in the area and is alternating. D) Tuff, this lithology shows the alternation of events in the area. E) Sandstone, which emerges at the base of the outcrop, near the stream.

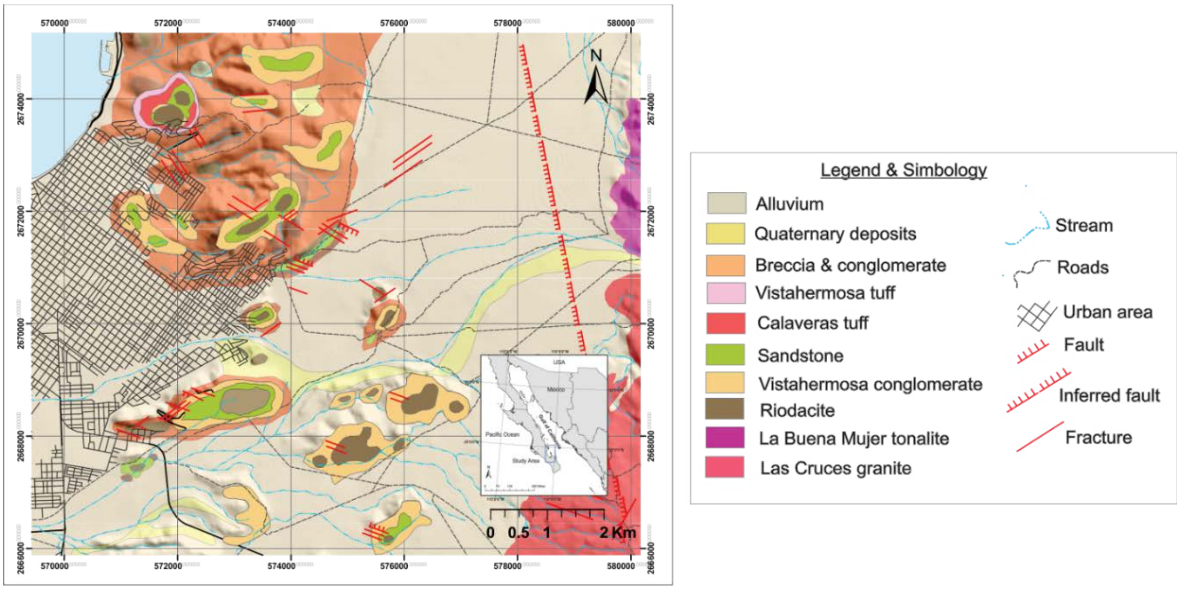


Figure 3: Location and lithology-structural map of the study area, where outcrops are generally displayed.

possible failures or fractures [Figure 5] in the form of diaclases in a system of three main orientations. Considering this, they were grouped into several data sets (Faults: N10 ° E / 28 ° SE, Fractures 1: N20°W / 50° SW, Fractures 2: S45 ° E / 85NE and Fractures 3: S70°W / 85° SE) and they were represented on stereographic diagrams to select the areas of greatest susceptibility.

Geological resistance index (GSI)

In most cases of rock removal processes, the resistance of the rock itself conditions the stability of the slopes and the resistance to the discontinuity planes they present. Figures 6-7 Estimation of the Geological Resistance Index, GSI, based on a Geological description of the Rock Massif [15]. Therefore, another complementary aspect was to calculate the susceptibility to planar landslides in rocks, (TOBIA kinematic method). This method relates the structural features of the lithology (diaclases, fractures, faults and stratifications) with the appearance and slope of the slope. In most cases of rock removal processes, the resistance of the rock itself conditions the stability of the slopes and the

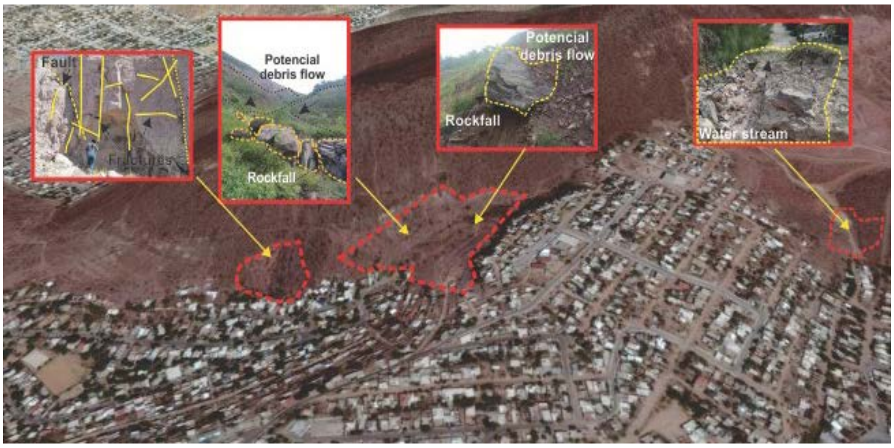


Figure 4: It shows normal failure and fractures that displaces the entire rock sequence and could cause reactivation of rock landslides (Image taken from Google Earth pro 2015).

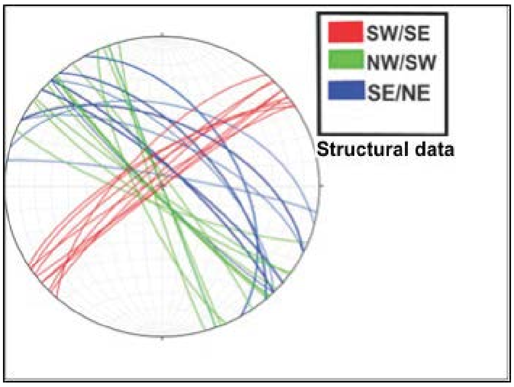
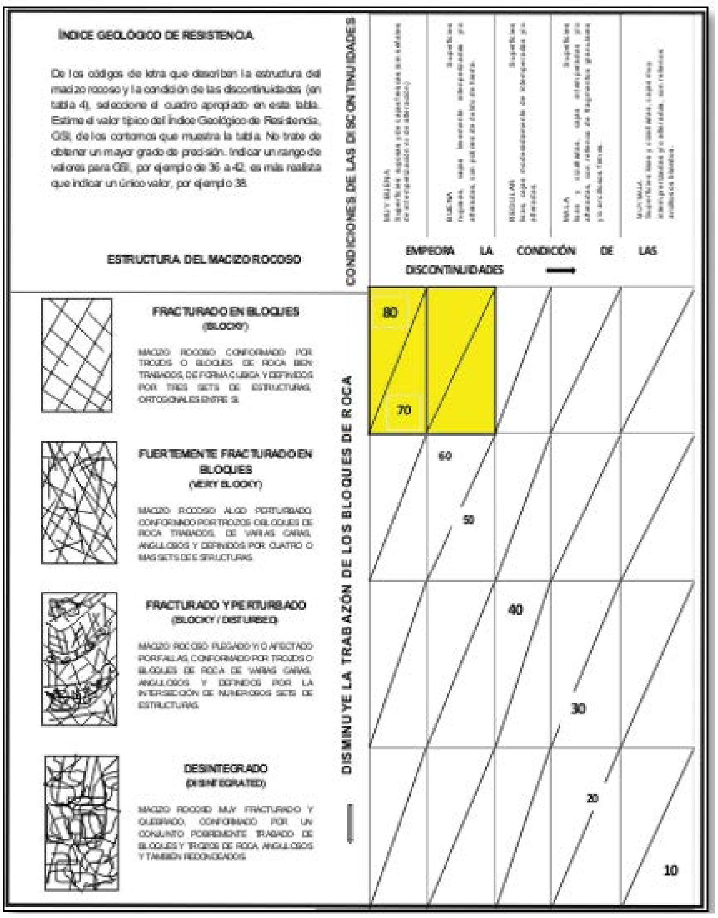
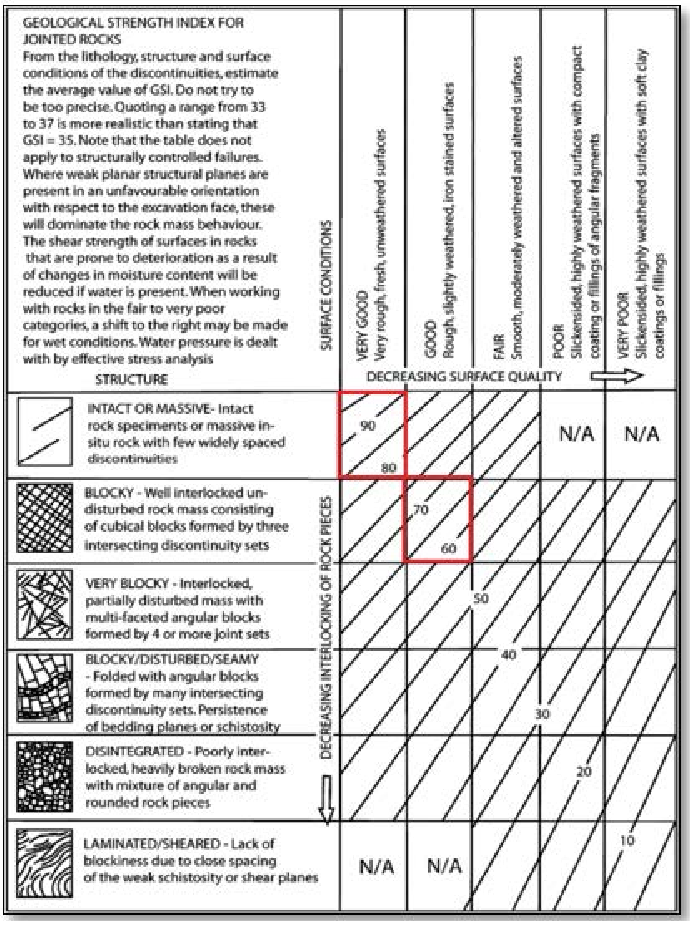


Figure 5: Stereographic projection of the structural behavior of the study area, where three alignment patterns are visualized.





Figures 6,7: Estimation of the Geological Resistance Index, GSI, based on a Geological description of the Rock Massif [15].

resistance to the discontinuity planes they present. For this case study, outcrops present different lithology (heterogeneous and discontinuous medium), which assign a geomechanical behavior that can be evaluated based on the methodology developed [1,15], based on the identification, description and classification of the mechanical characteristics of the structure based on two parameters: Fracture state and discontinuity surfaces (Quality of discontinuities), assigning values of geological resistance index (GSI) to each lithology recognized in the area [Figures 6- 7].

The GSI evaluation was performed by comparison with typical conditions, the value of the GSI varies between 0 and 100. You can define 5 rock quality classes [Table 1]:

* Very Poor Rock Quality (GSI 0 -20)

* Poor rock quality (GSI 20 - 40)

* Regular rock quality (GSI 40-60)

* Good rock Quality (GSI 60-80)

* Very Good rock Quality (GSI 80-100)

Considering the zoning at local level, the dominant lithology and geotechnical data for urban development, a complementary method should be applied to cartography and field geology that allows to evaluate the stability of the landslides and / or falls of rocks in a superficial way of the study area (Model called SHALSTAB in ARC VIEW environment), caused as a trigger for precipitation. This method is developed using geo-mechanical data considering the conditions of agreement that form the geology and / or edaphology of the study area (rock and soil) [Table 2]. The model allows evaluating different rain conditions or detonating events. In the case of the study area, an intensity of 150mm/hr was used, with a return period of 10 years according to the IFP curve (Precipitation Frequency Index) [16].

Geological and geohydrological risks

The urban settlement due to its physical characteristics is influenced by some phenomena with potential for affectation, which are described below:

Floods

Due to its climate, topography, type of soils and slopes, the Valley and city of La Paz characterizes its surface hydrology due to the lack of rivers or permanent surface flows. However, the extent of the basin is defined by intermittent streams originating in the Sierras de Las Cruces and El Novillo and the plain in which these runoffs are distributed until they flow into the Bay of La Paz, which are reactivated during the season of rainfall and hurricanes, constituting that important areas of flooding are generated in the area peripheral of the city of La Paz.

The Marquez de Leon urban settlement is located in the northwestern portion of the La Paz basin and it´s characterized by a stream that is crossed by a main stream of about 15m. wide and with irregular margins, that reach about 3m high. The right margin by compacted sand and fixed by endemic vegetation with a height of 1.5 meters and a shallow slope of about 15 °, while its right margin is constituted by fragmented rocks of large dimensions (4m long by 1.5 thick which is known as a protective work placed by the state government) and a maximum height of 2.5 m. [Figure 8]. This stream has a slope of about 25°. This aspect is significant in this town due to the proximity of the urban settlements to the creek, which varies from 20m to 80m apart, and without any civil protection work, that protects the new urban conditions of the colony. Due to these aforementioned characteristics, the importance of precipitation, geology and its relation to meteorological events are pointed out. These three factors affect the sediment transport process.

The lithology present in the area of this urban colony and the accumulation of deposits of sandy sediments from the Las Cruces mountain range are very significant, having as reference that the widest and deepest channels are filled with water more quickly. From the images, it is clearly observed that there are recent flood plains on the banks of the streams, which clearly indicate the potential for transport and deposition of sediments that occur in this colony [Figure 8].

Table 1: Fracture status and discontinuity surfaces (Quality of discontinuities), of the study area assigning values of Geological Resistance Index (GRI).

Lithology	RGI value	Rock quality
Riodacite	60-70	Good
Congalomerate	60-80	Good
Tuff	60-70	Good
Sandstone	60-80	Good

Sediment Samples (Alluvium deposit)	Geomecanic properties											
	Classification	% fine	% Sandstone	% Grave	% W	Density (p)	*L.L.	*P.L.	*P.I.	%DEVP kg/m³	%EVP	C kg/cm²	Friction angle (Ψ)
CML #1	SW	1.7	93.1	5.2	9.4	2.64	SR	SR	SR	1629	1789	0.253	31.6
CML #2	SP	0.9	96.1	3.0	1.2	2.62	SR	SR	SR	1612	1707	0.243	27.3
CML #3	SP	1.1	94.7	4.2	2.0	2.64	SR	SR	SR	1599	1698	0.349	26.2
CML #4	SP	1.0	97.3	1.7	1.9	2.63	SR	SR	SR	1607	1720	0.157	31.2
CML #5	SW	1.7	95.4	2.9	1.1	2.62	SR	SR	SR	1652	1780	0.285	30.6
Lithology													
Comondu Formation	Volcanic sedimentary rock	ND	ND	ND	2.8	ND	ND	ND	ND	ND	ND	28	0.5

Table 2: Geo-mechanical parameters of the soil where: C, cohesion; W, unit weight; φ, friction angle; ρ, density; L.L., Liquid limit P.L., Plastic limit; P.I.., Plastic index; % .DEVP., Dry empty volume percentage; % EVP, empty volume percentage.

Rock slide and rock masses removal

Within the study area, two rock movement processes were recognized: Rock mass removal and Rockslide.

Rockslide

The riodacitic composition blocks are located on a topographic slope of 25 ° and vary in dimensions. The distribution of these blocks is located in the upper and middle parts of the topography, with evidence of sliding in two ways: Therefore, the location of both processes was observed in the upper and middle parts of the topography, with the description of them being carried out in two groups:

a) Events that occur in the rock (materials of greater competition) that correspond to blocks of riodacitic composition that are located on a topographic slope of 25° and vary in dimensions from 2 to 4m in length, which approximate in a weight of 2 tons each.

b) Mass package of volcanic clasts that are classified as less competent materials. In particular, this category includes inconsistent material, corresponding to volcanic lithology (pyroclastic deposits not sold.

METHODOLOGY

The present study represents the first stage of a larger-scale project, which comprises several stages divided into different areas of the city of La Paz, in order to understand the geological-urban integral knowledge. The methodology used was based on the use of different geo-hazard characterization and zoning methods, due to the geological, mechanical and hydrological characteristics of the study area [Figures 9 and 10]. Due to the lack of inventory of events of landslides and/or falls of rocks, it was determined to apply methods used in a complementary way, both direct-qualitative methods, as well as indirect-quantitative methods. Direct-qualitative methods were applied through cartographic survey and recognition of aspects of lithology, geomorphology, structural geology (failures, fractures and diaclases), framed in regional tectonics.

On the other hand, indirect-qualitative methods consisted of the use of satellite images, aerial photography scale 1:50,000, tools of the Geographic Information System (GIS), which helped to detect, classify and zoning areas with potential geological and hydrogeological risks represented in relevant thematic layers belonging to the causal factors (Geomorphology, lithology, topography, stratigraphy, faults, fractures, drainage, precipitation etc.), with this several thematic maps were produced.

RESULTS AND CONCLUSION

The urban geology of the study area is characterized by an isolated sequence of outcropping rocks in its NNW portion, which are mainly constituted by volcanic and volcano sedimentary rocks. This lithology is grouped in the Comondú Formation recognized within the area in which its geomechanical condition and anthropic action stand out. The lithological conditions and their characterization are related to other factors (hydrogeological, hydrometeorological, and geomechanical) that generate mass and rock block removal movements.

Based on the above conditions, fall processes, landslides and / or rock flows were recognized. Of these two sets, only 26 slides in individual rock blocks and 2 in rock removal (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 *in* 1996. Being the failure mechanism and detachment mode 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 block runs reach 3 to tons of weight.

The distribution of these events were located within the slopes (slopes of 25° to 28°) and steep slopes of the topography, (25 ° to 28 °), which is limited by the stream that crosses the northern part of the colony Marquez de León and in turn coincides with some urban settlements as they are established in the very near margins of the hills and streams. This geohydrology and hydro meteorological condition denotes poor urban planning and high risk for its population when settled in flood zones. The results obtained based on this geotechnical characterization (Geological Resistance Index (GSI)) turn out to be very homogeneous and close in parameters, since it is a volcanic and volcano sedimentary lithology with a similar genesis in processes and evolution time. The geomechanical behavior of the lithology is based on the observations at the

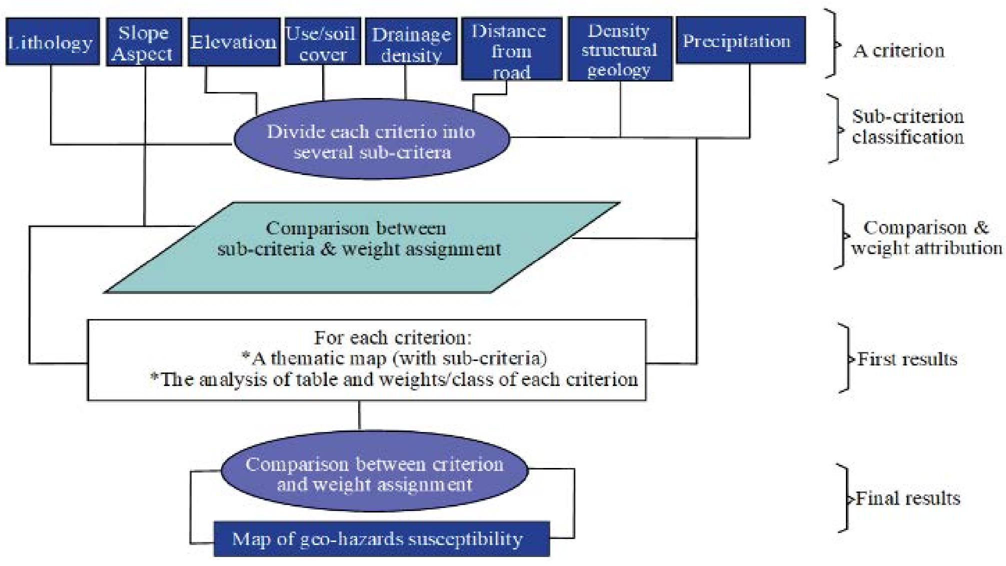


Figure 8: Methodology applied to the study area.

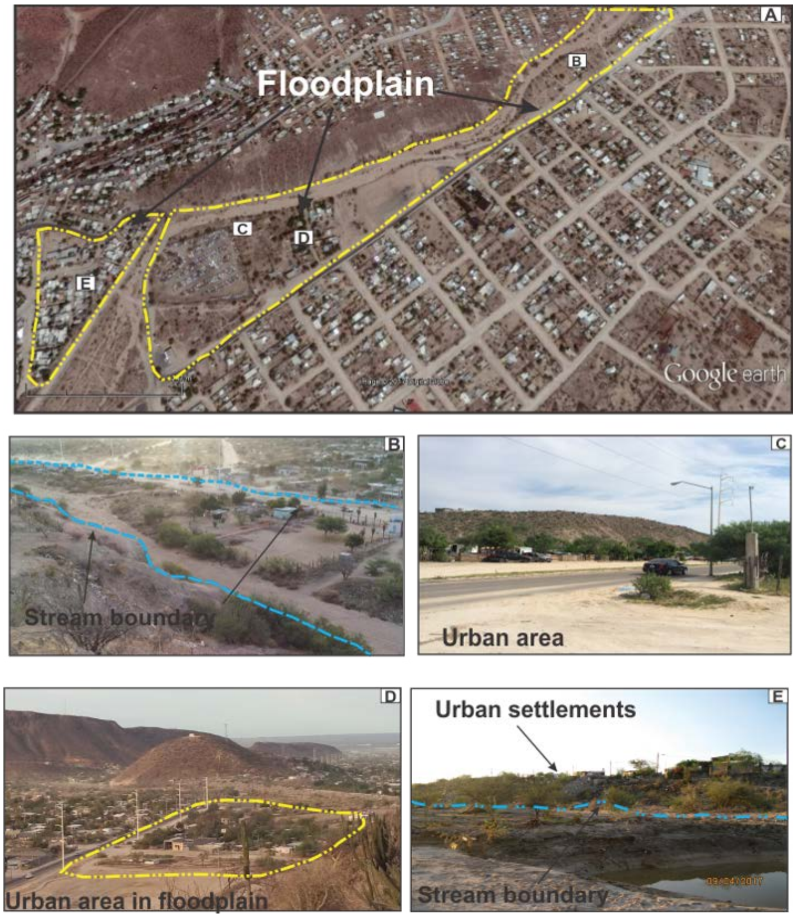


Figure 9: Image that highlights the deposit areas of sediments transported by the stream (Floodplains) .A) and B) Areas on the periphery of the colony where the limits of the stream channels are observed and that denote the proximity to the areas of flooding to the urbanized area C) and D) Images that refer to urban development invading the riverbed and its potential flood risk.

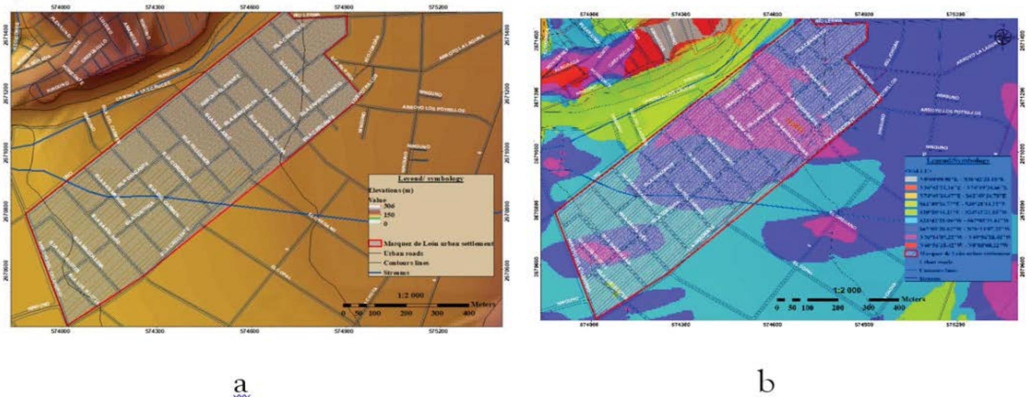


Figure 10: Thematic maps of the two factors involved in the landslide susceptibility analysis a) Elevation, b) Slope.

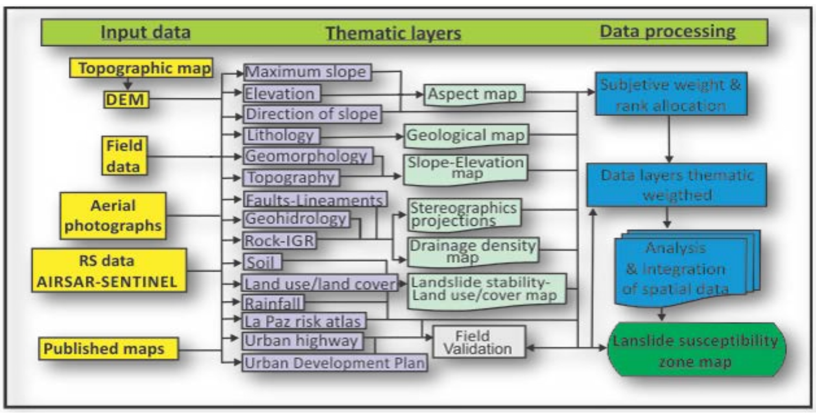


Figure 11: Methodology applied to the study area.

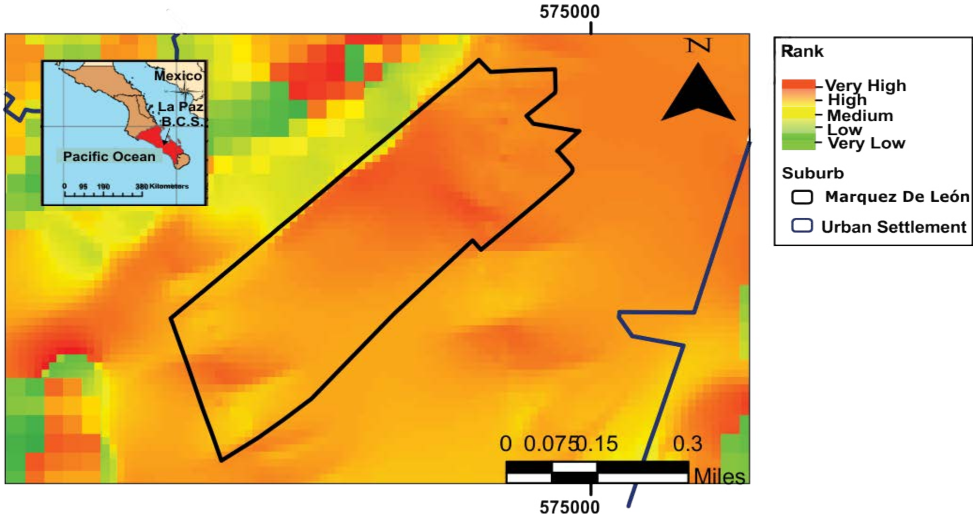


Figure 12: Geo-hazard susceptibility map of the Manuel Marquez de Leon urban settlement, La Paz, BCS, Mexico.

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 diaclases [Figures 3 and 4] . The conditions of the discontinuities are very good to good (range 70 to 80) since the surfaces are weatherproof [Figures 6 and 7]. The processes of removal of rock masses and rock blocks are delimited in the upper and middle part of the topography (100 to 50 meters above sea level) with 80% of events represented only by a single lithology: La riodacite. 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 results of this work will allow in the long term to make maps of susceptibility in geological risks focused on the scale of the city of La Paz, which in turn can be projected to other urban areas of the State of Baja California Sur. All this aims to form a geotechnical base tool to achieve a sustainable vision of our environment and physical environment that leads to a future urban-sustainable development of Baja California Sur State. The author thanks the Technological Institute of La Paz for the logistical support provided.

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