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Geo-hazards Associated with Urban Geology in the City of La Paz, Baja California Sur., Mexico

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Abstract:

Geology as a tool to identify areas of geological risk is useful to determine the relationship between the geological space and the sustainable urban development of a city. At the national, regional, and local level where the study area is located, there is a growing need to create new urban areas. However, these are not linked to an adequate analysis of the geology and the main factors that control risk conditions. Consequently, the risks and its impacts have been manifested due to different factors. The methodology to reach the objectives was based on the compilation of the existing information of the study area, data collection, and observation of the geohydrological conditions. All this information was complemented using RS (remote sensors) & GIS (geographic information systems) technology supported by satellite data prepared in Arcgis software. Finally, several thematic maps and a final map of risk vulnerability were generated. The results represent the first stage of a larger scale project to contribute new geotechnical knowledge to be used in the more precise zoning of geological and hydrogeological risks and that together they are useful for planning and building sustainable urban development of La Paz city.

1. Introduction[1]

Geological and hydrometeorological risks are currently responsible for high levels of affectation and destruction in urban areas. Only in the twentieth century, it is estimated that more than one million people worldwide have been killed as a result of earthquakes. In Latin America, these earth movements are constant and bring a secondary effect of landslides and rocks. The predictions of these landslides have received great attention and study due to the socio-economic impacts they produce [1–3], as well as for their usefulness as a tool urban planification.

The interactions between factors such as climate, topography, geology, soil, precipitation, vegetation, the mechanical strength of the rock (index of geological resistance) [4], and mechanical soil conditions play a very important role as trigger mechanisms to processes of removal, landslides, and fallen rocks. In addition to this, these conditions are influenced by the occupational conditions of the area in relation to the population and infrastructure, since the settlements located at the foothills and mountains are very vulnerable if the surface of the terrain with a pronounced slope is found with loose material and without vegetation cover; the problem becomes more acute if there is a channel in the high slope area [5].

In Mexico annually, more than 50% of the disasters that occur in the country are triggered by phenomena of hydrometeorological origin, highlighting hurricanes and other types of torrential rains, floods, droughts, frosts and hailstorms, among others [6]. In Baja California Sur, the state has an incidence of cyclones in average of a tropical cyclone of the Northeast Pacific and two approaches less than 300 km. Between 1966 and 2010, 39 cyclones arrived at the state, 20 of which have arrived in September [7]. In addition, if it is considered that the volume of runoff (11 Mm^3/year, product of a precipitated volume of 351 Mm^3/year) by the streams that make up the La Paz Basin extend and cross the urban zone with low speeds [8].

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 works by various authors and institutions at the regional and local geology level [9-14]. More recently in the work done by Pérez-Venzor, 2013 [15], a geological-geochemical study of the Southern portion of the State (Los Cabos Block) refers to the present study area as part of a Plutonic Geological Complex of La Paz.

The government has undertaken isolated studies of the location of risk areas in a general way. In the official documents of the urban development plan (UPD-2018) of the city of La Paz, as well as in the municipality of Los Cabos [16], Baja California Sur, and recently in the 2012 Atlas of Natural Risks was elaborated upon at the state level.

Therefore, a more precise geological recognition is required on a scale (urban suburb) where the possible geological risks and the risks derived from hydrometeorological events are characterized and identified.

All previous antecedents are focused in different objectives of geological character, but there is little investigation of regional and local form that includes the urban geology directed toward geological engineering and applied geotechnical purposes. For example, in Guaymas, Sonora [17], where the area was characterized based on local geology in several aspects and several thematic maps were developed, while in the city of Tijuana Baja California, a diagnosis of urban risks was made [18] with a geological characterization of the city.

One of the most important measures for the prevention and reduction of losses by mass movements refers to the zoning of the territory's susceptibility and threats. Therefore, a systematic mapping of the most susceptible areas is needed, these being defined, usually expressed in a cartographic form that is generated with the support of GIS (geographic information systems), satellite images, use of the slip SIM (susceptibility index method) and field geological work.

The objective of this study was to zonify the geo-hazards associated with urban geology based on areas susceptible to landslides, fallen rocks and flood-prone areas, in the northwest portion of La Paz using RS and GIS techniques.

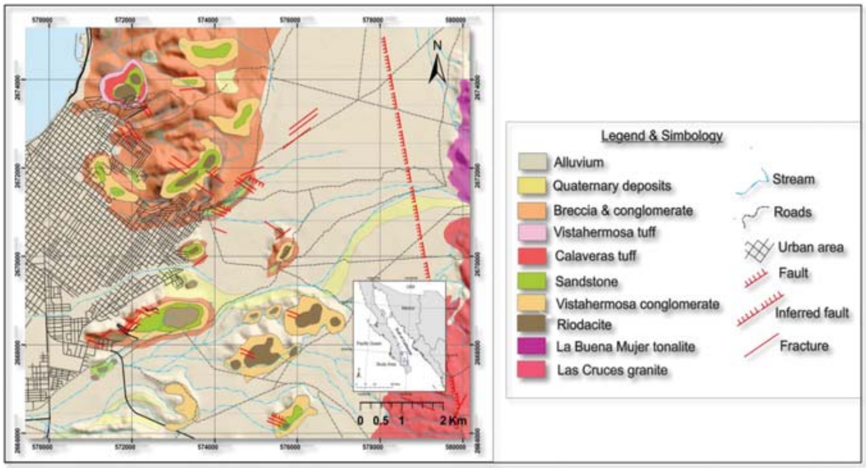

Figure 1. Location and lithology-structural map of the study area, where outcrops are generally displayed

2. Study Zone

La Paz, capital city of the state of Baja California Sur, is located in the southern portion of the Peninsula of Baja California, Mexico. Within the Köppen classification, the dominant climate is very dry and very warm, with an average annual temperature between 22°C and 24°C, with rainfall in summer and winter mainly, where the winter precipitation is 10.2%, with great influence of atmospheric disturbances originated in the Pacific Ocean of cyclonic type that produces very intense precipitations. The city of La Paz is characterized by a morphology dominated by basins and sierras, resulting from the interaction of magmatic-tectonic processes, which is settled in Holocene deposits that correspond to the alluvial material (varying from sand to sandy gravel) of the active streams, where the thickness of the material varies and can reach a few meters in the main streams [19]. Geologically, volcanic and volcaniclastic rocks (sandstone and volcaniclastic 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 [20-24]. The city of La Paz has a population of 251,871 [25]. The study area (163.89 km^2) is located in the northwest portion of the city of La Paz, between the coordinates UTM 12 R 570000-580000 N and 2666000-2674000E (Fig. 1).

3. Methodology

The present study represents the first stage of a larger-scale project, comprising several stages divided into different areas of the city of La Paz, in order to understand the comprehensive geological-urban knowledge. The methodology applied was the AHP (analytic hierarchy process) development by Saaty (1980) [26], which consists of matrix analysis and involves value judgments. In this way, the matrix of preference over the selected criteria was generated, obtaining the weighting of the eight chosen variables. It was important the knowledge of the study area, the documentation and local studies generated to date, where the criteria of the specialists are taken up.

3.1 Estimation and Numerical Assignment of Slip Factors

The determination of the numerical assignment of the landslide risk assessment factor is a numerical system that depends on the relevant factors. By superimposing the elements or parameters indicating threats and/or risks, a zoning map of landslide susceptibility can be drawn up, delimiting the risk areas, giving each factor a specific weight and value, and analyzing the situations site by site, with the help of the various thematic maps [27].

For this reason, factors specific to the physical environment were identified for the study area and numerical values were assigned to the factors based on the degree of influence on the instability of the slope. The different classes within each causative factor were also assigned values according to their influence in causing instability, in order to give a more precise assignment of each causative factor and its respective subclasses.

The relevant factors for the zoning mapping of susceptibility to landslide risks include lithology, slope, elevation, use and land cover, density of urban roads, lineament density, drainage density, and precipitation.

The stability of an area is multifactorial and the behavior of each factor has different degrees of influence, so the maximum numerical estimate of the slip hazard evolution factor for different categories is determined based on its estimated importance to cause instability. The important factors responsible for the area of landslides were assigned numerical values (range) on a scale of 1 to 5 in order of importance. The rating was assigned to the classes of the factors in ordinal scales from 1 to 5, where a higher rating indicates a greater susceptibility to the occurrence of landslides.

This part of the methodology is the basis for giving weight (wi) to each parameter and defining its relative importance to induce landslides (Ri). These weighted factor maps were superimposed using a multivariate criteria analysis (Table. 1) to prepare a risk susceptibility map (RSM) for the present study area [28].

3.2 Data Used

In this study, various types of remote sensing data were used to detect characteristics of landslides, for example, remote sensing products stereo, which revealed the actual morphodynamic characteristics of the areas susceptible to removal and fallen rocks for EOS (Earth Observing System) data and Landsat 7-8 (2014-2018). In addition, published reports, field studies, and interpretation of digital aerial photographs (FAD) (50,000 scale 10,000) were used. This data set was compared with the landslide characteristics generated from aerial photographs and satellite images (WorldView-4) (November 2016), which are also generated in the UTM reference system.

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

No	Factor	Class	No.	Weight (*wi*)	Index	Observations
1	**Lithology**	Alluvium	1	20	20	The lithology with greater susceptibility to slip is the riodacíte, for its high fracturing and accumulation of rock masses
		Sandstone	2		40	
		Tuff	3		60	
		Conglomerate	4		80	
		Riodacite	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 direction of the slope are North, Northeast and Northwest are located in the high parts of the relief where the areas of removal and fallen rocks and are located.
		10.8–21.6	2		32	
		21.6–32.4	3		48	
		32.4–43.4	4		64	
		Higher to 43.2	5		80	
3		0.0–76	1	15	15	The highest elevation is located NE of the city increasing the possibility of landslides, rockfalls, and floodplains.
		77–153	2		30	
		154–229	3		45	
		230–306	4		60	
		307–382	5		75	
4		Urban Settlements	3	14	14	The use of soils dominates by its use in housing, with surrounding areas of soil and endemic vegetation.
		Urban Zone	2		28	
		Forest Soil	1		42	
5		0.0–59.7	1	12	12	Drainage flows through the urban center of the study area, which denotes its risk influence.
		59.7–119.4	2		24	
		119.4–179.2	3		36	
		179.2–238.9	4		48	
		238.9–298.0	5		60	
6		0–5.6	1	10	10	Landslides in forms of removal 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	
		22.4–28.0	5		50	
7		0.0–6.0	1	8	8	Fractures, stratigraphy and foliation plans are a factor to consider in the vicinty of inhabitated areas.
		6.0–8.0	2		16	
		8.0–9.0	3		24	
		9.0–21.0	4		32	
		21.0–25.0	5		40	
		<100	1		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 presents the rainfall in periods of decade.
		>100	2		10	

3.3 Mapping Risk Vulnerability

The risk vulnerability map is based on a ZLR (zoning of landslide risk - rock removal, debris flow and falling), 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) = Σn i = 1 (*wi* * *Ri*)

Where *wi* denotes the weight for the factor *i* and *Ri* denotes the classification of the factor i. In this study, the total number of factors (*n*) is 8, where the 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 ZLR was calculated as follows:

Value ZLR = L + SL+ EL + SL/U-SL + DD+ URD + SD + 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 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 using the Arcgis software, several thematic maps based on and related to the DEM (digital elevation model) were generated: General geological map, elevations, slope, aspect, drainage, land/vegetation use, precipitation and as a final product, a vulnerability map.

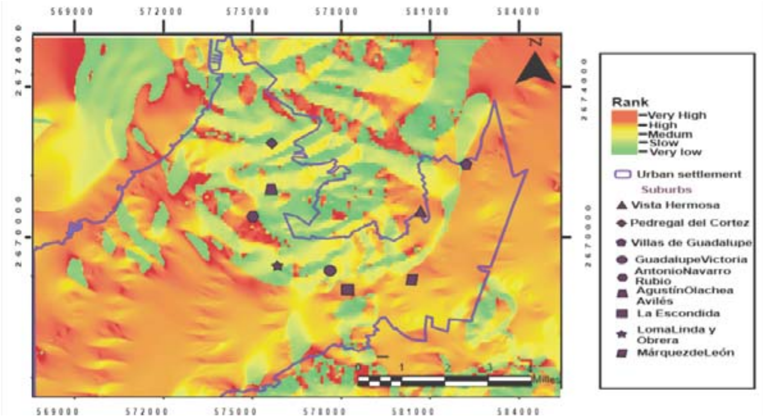

Figure 2. Map showing the vulnerability by urban settlement

4. Results

4.1 Geological and Geohydrological Vulnerability

The physical characteristics of the study area are influenced by some phenomena with potential for affectation, which are described below:

4.1.1 Floods

Due to its climate, topography, soil type, 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 extension of the basin is defined by the intermittent streams originated in the Sierras de Las Cruces and El Novillo and the plain in which these runoffs are distributed until their discharge into the Bay of La Paz, which are reactivated during the rainy and hurricane season, constituting important flood areas in the area peripheral of the city of La Paz (Fig. 2).

4.1.2 Landslides and Fallen Rocks

Within the study area, two processes of rock movements were recognized:

(a) Landslides (Removal rocks, debris flow)

(b) Fallen rocks

The distribution of these events was located within the middle and high portions of the topography (328 to 164 ft above sea level and slope of 25° to 28°), which is limited by the streams that cross most of the urban settlements (Fig. 3). Processes susceptible to landslides in the whole area were recognized (26 debris flows and 12 rockfalls).

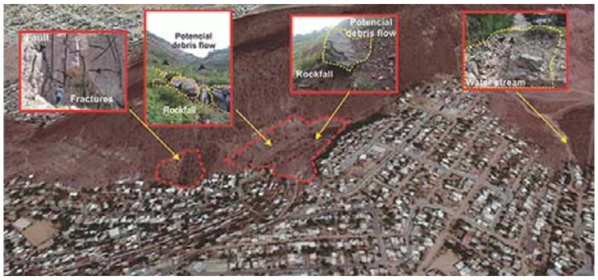

Fig. 3. Photographic series supported by satellite image to illustrate some sites of potential susceptibility to landslide and fallen rocks

La Paz city is conformed by 278 urban settlements and the analysis of the study area shows nine sites with low to very high degree vulnerability (Fig. 3). The characteristics of risk vulnerability are described below:

(a) Rock slides that behave as a package of masses of volcanic clasts and that are classified as less competent materials. In this category, incoherent material is included, corresponding to the lithology of volcanic origin (pyroclastic deposits not welded by rhyodacite) and the rest of the material (sandstone and conglomerate sandstone) somewhat weathered.

(b) Events that have occurred properly as falling rocks (materials of greater competition) that correspond to blocks of rhyodacite composition that are located on a topographic slope of 25°-28° and vary in dimensions from 2 to 4 m in length, which approximate in a weight of 3 to 10 tons each (Fig.3).

(c) Using the AHP, the LSI values were computed by using equation [1]. The LSI values are divided into five classes based on the natural breaks range, which represent five different zones in the landslide susceptibility map. These are VLS (very low susceptibility), LS (low susceptibility), MS (medium susceptibility), HS (high susceptibility), VHS (very high susceptibility) and the percentage of area covering each susceptibility class are shown in Table 2.

From the analysis (Table 2 and Fig. 4), it is evident that 18.6% of the total area fall under the VHS, 14.99% to HS and, followed by medium susceptible zones (18.77%), LS (23.38%), and very low susceptibility VLS (24.26%).

Table 2. Distribution of Areas and Percentages that Represent the Susceptibility of Geohazards in the Study Area

Landslide Susceptibility Class	Area (Sq. km)	Area (%)
Very Low (VLS)	39.77	24.26
Low (LS)	38.32	23.38
Medium (MS)	30.77	18.77
High (HS)	24.56	14.99
Very High (VHS)	30.47	18.60
Total Area	**163.89**	**100.00**

5. Discussion

The results and the methodology of this research work was the generation of maps of vulnerability (susceptibility) in geological risks focused on different geological issues of the urban and suburban area, which 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 and stream flooding areas are currently located, as well as hill slopes, with processes susceptible to landslide.

The location and description of the phenomena were carried out in two groups: the one of those that occurred in rock

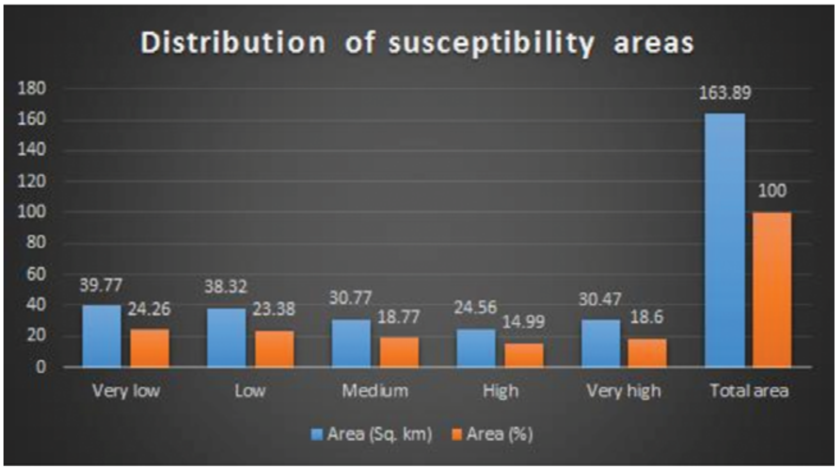

Figure 4. The zonation in terms of landslide susceptibility of the study area.

(materials of greater competition) and those that occurred in rocks of less competent materials. In particular, in this category incoherent material, of volcanic origin (non-welded pyroclastic deposits) and very widespread material, including immature soils is included. Of these two sets, 12 landslides (rockfall, removal) were identified on rocks and 26 in soils (volcanic deposits or severely overwhelmed rocks). The rock movements found in the area correspond mainly to the classification of Dikau [29] to fall processes, simple transitional slides and blocks.

The movements were generated from the 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.

This aspect of the results coincides with the research carried out by Momeni et al. [30], when affirming that in landslides and fallen rocks, slope and appearance play an elementary role in the flow of material since the slope provides speed and appearance indicates the direction of that slope.

6. Conclusions

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.The methodological proposal also complements the results obtained with a new landslide susceptibility map, which did not exist until the present date and defines areas of sensitive urban development at the urban settlement scale. The conclusions of this research work are presented below:

The conditions of the physical environment, which were used to weight the most influential factors for the susceptibility of landslides (Removal rocks, debris flow & rockfall), can be inferred that lithology, slope, and geomorphology (elevation) are the most dominant factors.

Based on the analysis of the most influencing factors to landslide activity (judged from their associated weights) are lithology (20), geomorphology (16), slope (15), land/use cover (14) drainage density (12) and the three least influencing factors are density of urban roads (10), density of structural features (8), and rainfall (5).

In terms of criticality and based on the validation of the susceptibility maps obtained, 33.59% of the total area presents geo-hazard susceptibility conditions from high to very high.

The percentage of very low to medium susceptible areas is close to 66.41% maximum.

The results represent a first stage of a larger scale project and with this it is possible to contribute new geotechnical knowledge to be used in the more precise zoning of geological and hydrogeological risks and that together they are useful for the planning and sustainable urban development of La Paz city.

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Notes

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