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## **Location of the Rainfall Recharge Areas in the Basin of La Paz, BCS, México**

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Additional information is available at the end of the chapter

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### **1. Introduction**

Rains are very scarce in the state of Baja California Sur, México, with an annual average of 175 mm (SARH-CNA, 1991). The basin of La Paz records a mean annual precipitation of 265 mm/year (CNA, 2005). Rainfall occur in torrential of short duration during the cyclone season (late summer and early autumn), which not only causes flooding, but because a large amount of water falls in a short time, it drains quickly towards the sea. Anyhow, infiltration is carried out, allowing aquifer recharge. Even so, available water for the population and agricultural irrigation is groundwater, which is pumped from the aquifer.

Due to an increased water demand, water availability from aquifers in the state of Baja California Sur, has been decreasing rapidly, mostly because of an inadequate management as it pumps more water than the supplied by natural recharge. This is the reason why most aquifers, in the state, are over-exploited.

An example of over-exploitation takes place in the agricultural valley of Santo Domingo, located about 120 miles North of La Paz, but now this serious situation is about to happen in the aquifer of La Paz.

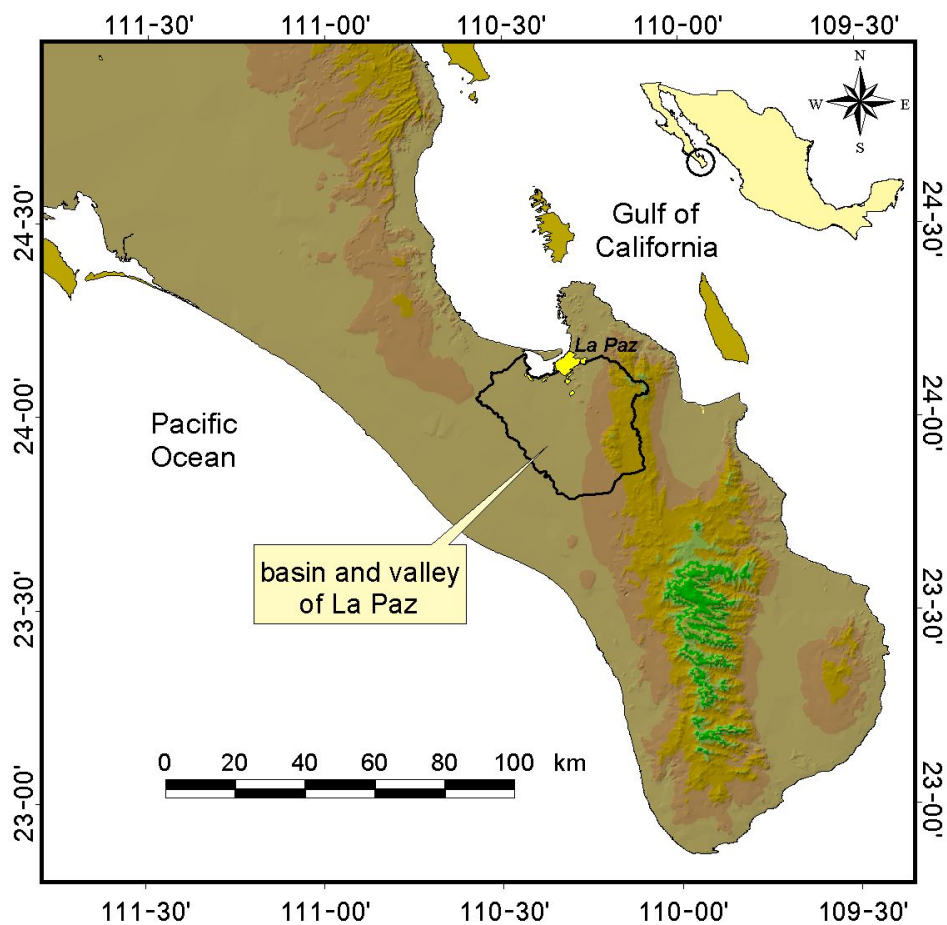
For the sustainability of these aquifers, it is necessary, among other things, to handle a strict management program (that does not exist at present). It is necessary to maintain a balance between recharge and exploitation, and also to protect recharge areas to avoid reducing the volume of rainwater that infiltrates into the ground.

Groundwater recharge is a process by which surface water or rainwater percolates through the soil to the level of groundwater to supply water for aquifers (Davis and Wiest, 1971).

This recharge is essential to basins and aquifers for water storage, especially in regions of high water demand, in arid zones without rivers or lakes, and where water is essential to economic development.

The city of La Paz is located at the Southern tip of the peninsula of Baja California (Figure 1). For years the source of freshwater supply for the population and agriculture has been obtained from groundwater exploitation of the aquifer of La Paz, but in recent years due to increased water demand by population growth, the aquifer is in over-exploitation condition (CNA, 1997).

The basin of La Paz collects 410 Mm<sup>3</sup>/year of rainfall, from this, evapotranspiration is about 80%, 16% infiltrates into the ground for aquifer recharge, and 15 Mm<sup>3</sup>/year runoff to the sea (Cruz-Falcón et al., 2011).



**Figure 1.** Location of the study area

For estimating groundwater recharge, literature describes several methods. However, these methods are not clearly defined and ordered (Sophocleous, 1991; Kommadath, 2000, Bridget et al., 2002), but can be grouped in two general classes, potential and real methods. Generally each method is related to another, so none is completely independent.

To choose an appropriate method, it is highly dependent on climatological information and water table. In the best case, depending on existing information and field work, the most suitable is a combination of potential and real methods (Bridget et al., 2002).

Estimation of recharge in a hydrological basin or an aquifer involves some complexity, due to the physical features of the area, availability of information, quality of data, and the method used.

The process of groundwater recharge consists of water flow from surface to subsurface, which is basically determined by infiltration capacity of the sediment layers and rocks. Infiltration depends on several factors such as the permeability of the materials, soil texture, moisture content, vegetation cover, land use, air entrainment, fine material washing, and soil compaction (Aparicio-Mijares, 1992). Also the climate, rain, slope, type of rock and sediment, play an important role in this process.

Normally groundwater recharge calculation is done by taking water level data and the water table fluctuation, supported by aquifer parameters such as transmissibility and storage coefficients.

A system of any hydrological basin can be described by a balance which considers water inlets and outlets. The main component of this system is the precipitation, but because all other components are related to each other, groundwater recharge, that can be vertical (from rainfall) or horizontal (from groundwater flow) is essential for aquifers supply (Peña-Haro and Arcos-Hernández, 2004).

In the basin of La Paz, rainfall recharge is the most important inlet component, although there is a small agricultural irrigation recharge, and a little artificial recharge caused by a dam located Southeast of the city of La Paz.

Because vertical recharge normally occurs in a stratified soil where hydraulic conductivity is variable, infiltration will depend on soil constitution, so it will be different if soil is formed of gravel, sand or clay.

For rainwater to infiltrate soil surface, soil must have some favorable conditions for this to happen. For example, an area devoid of vegetation will be freely exposed to direct impact of raindrops. This can substantially compact the soil and introduce simultaneously tiny particles inside the cracks and open ducts, which result in an immediate reduction of infiltration. By contrast, a dense covering of vegetation protects the soil surface allowing a better infiltration (Davis and Wiest, 1971).

Plant roots also help to keep soil open, thereby increasing infiltration. Infiltration occurs easily over unconsolidated soil or sediment, with coarse texture, especially if they are covered with vegetation. In consolidated soil, infiltration occurs if it is degraded by environment, or in areas where fractures or faults are present (Davis and Wiest, 1971).

In some of geohydrological studies conducted in the valley of La Paz, it is mentioned about the aquifer recharge areas. Most agree that these areas are located to the East and South of the basin, but none of these studies show them geographically on the map.

The SARH-UNAM-UABCS (1986), define a rainfall area in the Eastern portion of the valley of La Paz, a recharge area at the middle of the valley, and a rainfall water collecting - infiltration area Westward. They mention that groundwater recharge comes mainly from the Valley of El Coyote (North), from the elevations on the Western side the basin, and from the Southern portion of Sierra El Novillo (Southeast). The IPN-CICIMAR/CIBNOR/UABCS (2002), reports that the main aquifer groundwater recharge comes from the East side of the valley of La Paz, as a result of infiltration of surface runoff. CIGSA (2001), mention that the flow pattern determines that recharge areas are located at the West and South of the valley of La Paz.

A technique for recharge estimation (qualitatively), using some of the physical parameters involved in groundwater recharge, in a simple and practical way, is the method of 'weights'. This method can handle the parameters and some physical factors according to the characteristics of each area, by judgment and experience of the researcher, what distinguishes its applicability in the study of surface water and groundwater.

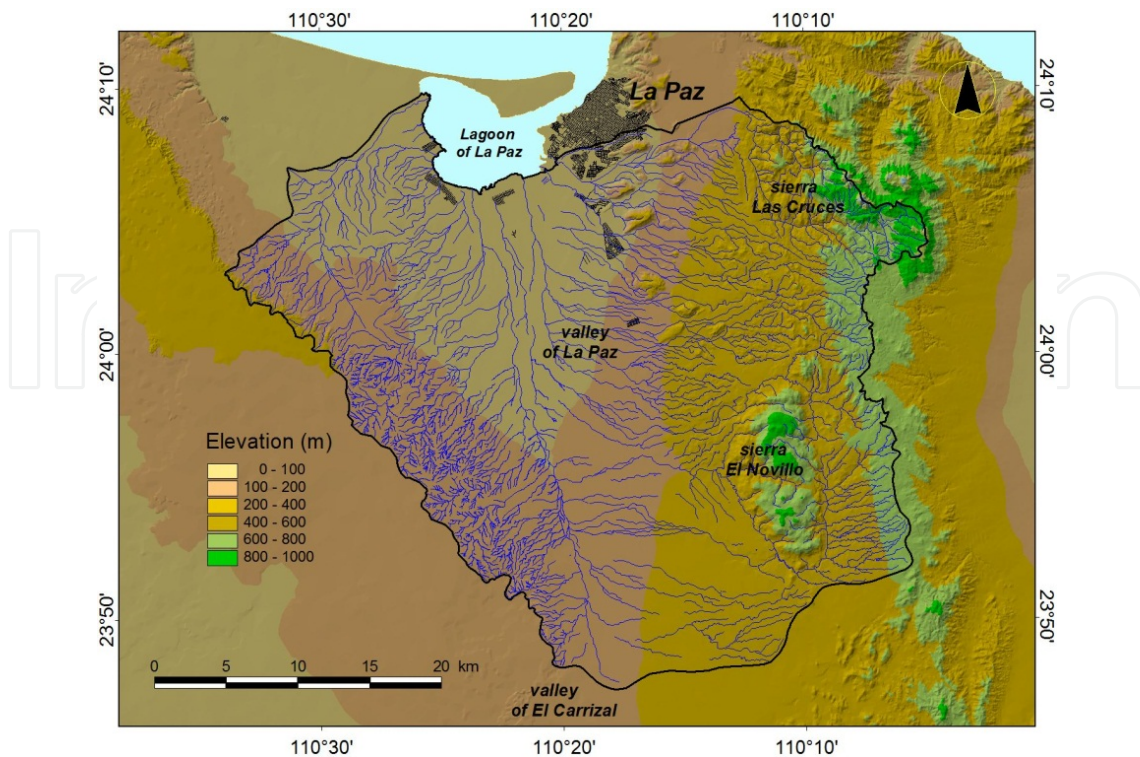
This study identifies the potential rainfall recharge areas in the basin of La Paz, with a geographic information system (GIS) from physical parameters such as terrain slope, geology, geomorphology, soils, land use and vegetation, runoff and precipitation. Through spatial analysis raster models are generated. The classes of each model are reclassified, and weights are assigned, using a criterion of logical reasoning where a greater or lesser number is assigned according to the importance of each class in contribution to groundwater recharge.

## 2. Study area

The basin of La Paz is located in the Southern portion of the peninsula of Baja California, which the city of La Paz is settled (Figure 1). The climate in this area is predominantly dry with an average temperature of 20-26°C, with higher temperatures in the months of July, August and September, sometimes reaching 40 to 45°C. The average annual rainfall in the basin is 265 mm (CNA, 2005), which occurs mostly during the summer, with the highest precipitations in August and September. In late summer occur tropical storms and cyclones. These events bring heavy rainfall, that contribute to recharge the aquifers all over around.

### 2.1. Basin of La Paz

From a physical point of view, a hydrological basin is defined as a surface in form of depression that collects rainfall water. Part of the rain that falls evaporates, another part infiltrates into the ground, and the remaining, once the subsurface is saturated, runoff to the plains, which may be a lake, river or the sea (modified of SEMARNAT, 2001). The delimitation of the basin of La Paz used in this study was defined by Cruz-Falcón et al. (2011). It extends approximately in an area of 1,275 km<sup>2</sup>, located between 23° 47' 24" to 24° 10' 12" North and 110° 04' 48" to 110° 35' 12" West (Figure 1). All runoffs end up into a coastal lagoon known as Lagoon of La Paz (Figure 2).



**Figure 2.** Delimitation of the basin of La Paz, and terrain elevation model (TEM).

### 3. Methodology and results

To locate potential rainfall recharge areas in the basin of La Paz, it was used a geographic information system (GIS) fed with vector information of physical parameters such as topographic slope, geology, geomorphology, soils, land use and vegetation, and precipitation. By spatial analysis, these layers of information were converted to images with a spatial resolution of 100 m.

To identify and locate rainfall recharge areas, it was used the 'weight average method' (Katpatal and Dube, 2004), which can be just called 'method of weights'.

The classes of each model were reclassified, and weights were assigned to each of them. The criteria for assigning weights to each class were based on a logical reasoning approach that considers weight a greater or lesser number according to the importance of each class as a contribution to groundwater recharge (Katpatal and Dube, 2004).

The assignment of weights to the different classes is based on an arbitrary scale, but considers the importance of each class as a contribution to groundwater recharge. The higher the number assigned, greater the contribution to groundwater recharge, and vice versa. In some cases, the same number could be assigned to different classes since their contribution to recharge is considered the same.

Once weights were assigned to the classes of the different parameters, it was generated a new model. Finally, the new models of the different parameters were integrated to generate a representative model of rainfall recharge areas in the basin of La Paz. This model contains seven classes that represent from a poor (1) to very good (7) contribution to groundwater recharge.

Weights assigned to the classes of each parameter are shown in the corresponding models (Figures).

### 3.1. Data used

Data come from 1983 available Geology mapping Charts from INEGI (National Institute of Statistics, Geography and Informatics) 1:250,000 scale. Soil, Land Use and Vegetation mapping Charts (2000), from INEGI, 1:250,000 scale. Geomorphology map (2004), from CONABIO (National Commission for Knowledge and Use of Biodiversity) 1:1,000,000 scale. Elevation contours and runoff (1998-2003) to generate elevation model, come from Charts of INEGI, 1:50,000 scale. Precipitation model comes from Cruz-Falcón et al. (2011).

For all processes, program ArcView 3.2 was used.

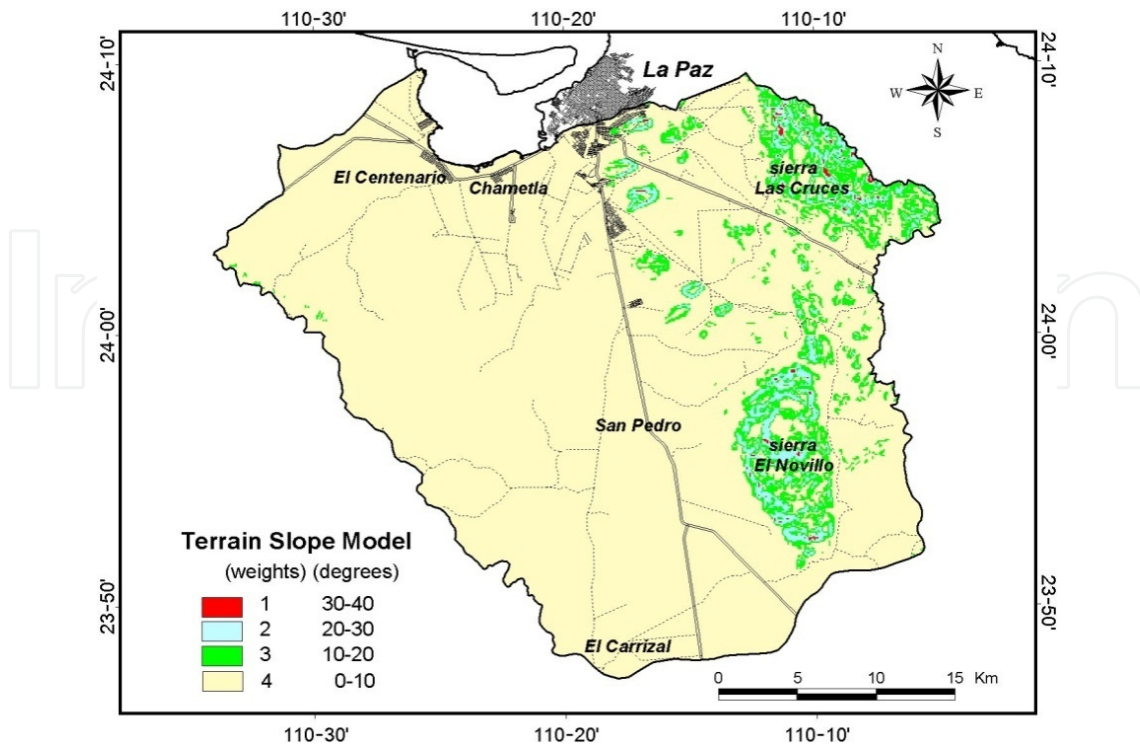
### 3.2. Criteria and models

From the terrain elevation model (TEM) (Figure 2), generated with ArcView tool and contour mapping of INEGI (1998-2003), it was obtained the terrain slope model (Figure 3). The terrain slope is the angle in degrees from horizontal. For this model there were considered four classes, of which the smallest angle has a greater contribution to recharge and vice versa.

From Figure 3, is observed that terrain slope with an angle of 0 to 10 degrees covers most of the basin.

For the geology model (Figure 4), it was considered the type and physical condition of rock. Rocks located near the coast, and consolidated volcanic material was assigned a smaller number. For consolidated sedimentary materials was assigned a slightly larger number. To metamorphic, weathered and fractured intrusive rocks, as well as for alluvial deposits, was assigned a number of medium to high.

Álvarez et al. (1997), describes the geology of the basin of La Paz characterized by a sequence of marine sediments and alluvial recent fans formed by conglomerates, sandstones and shales. Towards the NNW of the valley the Middle Tertiary to Recent sequence is formed by: San Gregorio Formation (Late Oligocene–Early Miocene) with an alternation of tuff sandstones, silty shales, mudstones, conglomerates and stones and fosforite inter-bedded layers; San Isidro Formation (Early Miocene) formed by glauconitic sandstones, conglomerates, shales and some pink colored rhyolitic tuff layers; and Comondu Formation (Late Miocene) formed by sandstones and volcanic conglomerates, rhyolitic tuffs, and esitichars and lava flows. Towards the NNE, emerge rocks from Cretaceous to Recent that constitute the sierras Las Cruces and El Novillo (Figure 4), formed by intrusive rocks such as granite, gabbro and tonalite.



**Figure 3.** Terrain Slope model of the basin of La Paz.

In this study, due to the physical condition of igneous rocks as granite (KGr) that is quite fractured and weathered, it was assigned a higher number than for alluvial deposits (Qal). Gabbro (KGa) also was considered fractured and weathered.

From Figure 4, is observed that Quaternary material such as sandstone (ar), conglomerate (cg) and alluvium (al), are distributed in the middle of the basin, and metamorphic rocks (gneiss and schist) and igneous rocks (gabbro and granite) are located to the East and South-east.

To assign weights to the classes of the geomorphology model (Figure 5), there were considered the hydro geomorphological features of the basin. Valleys (piedmont and plains) with gentle slope and low drainage were assigned with high infiltration rate, compared with mountains and hills with regular infiltration rate, and structural terraces with lower infiltration rate.

From Figure 5, is observed that most of the basin is characterized by piedmont and cumulative plains, except to the East and Northeast that is defined by mountains and hills.

For the land use and vegetation model (Figure 6), weights were assigned from two criteria, one that assumes vegetation can retain more rainwater for allowing infiltration, and the other, that urban areas and man-made infrastructure is where runoff predominates. Eventually, for high and dense vegetation was assigned a higher number than for small vegetation, as well as grassland and halophyte plants. Urban areas were assigned with lower number because there is no infiltration.



From Figure 6, is observed that in most of the basin predominates sarco-crasicaule and sarco-caule bush, except to the East and Southeast that is characterized by low forest.

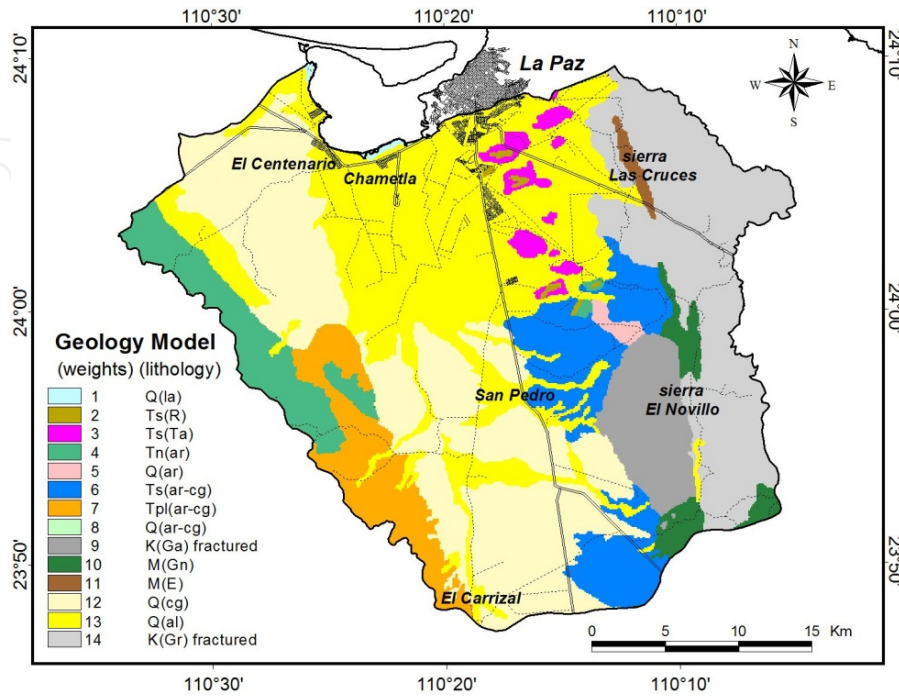


Figure 4. Geology model of the basin of La Paz.

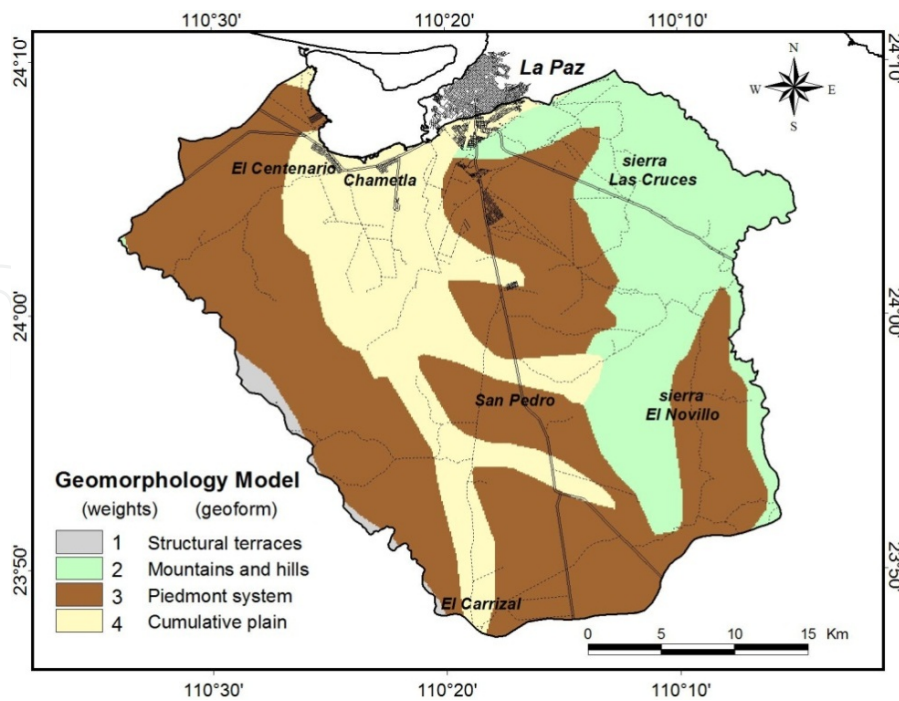
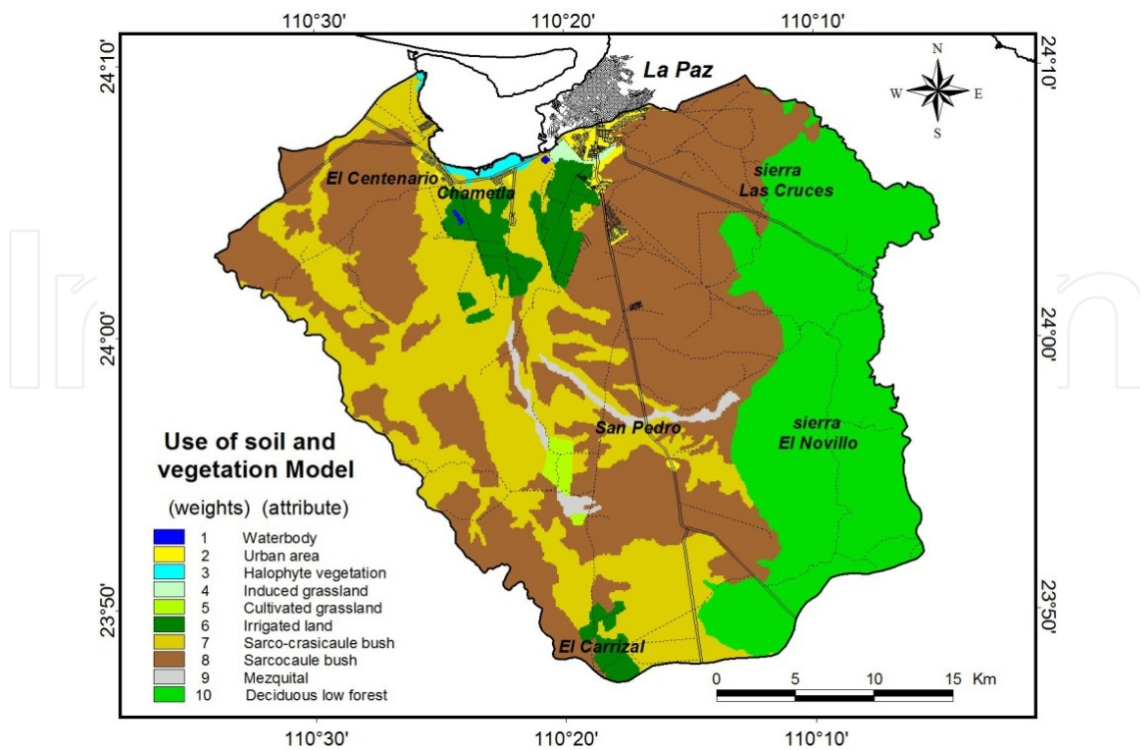


Figure 5. Geomorphology model of the basin of La Paz. Intermittent streams are shown (blue lines).



**Figure 6.** Use of Soil and Vegetation model of the basin of La Paz.

For the edaphic model (Figure 7) there were considered the different types of soil for the assigning of weights.

Regosol is the soil which was assigned a higher number. This soil is common in desert and dry tropical areas, it is the most abundant soil of the alluvial deposits that fill the basin. Litosol, despite of being a soil forming a very thin layer, it allows a rapid infiltration to subsurface layers. Fluvisol, usually common in alluvial deposits, has a very fine texture that diminishes infiltration capacity. Solonchack, is a predominantly saline soil that extends very close to the coast of the lagoon of La Paz. Xerosol, is a very fine soil rich in clays, that because of its texture, infiltration is reduced.

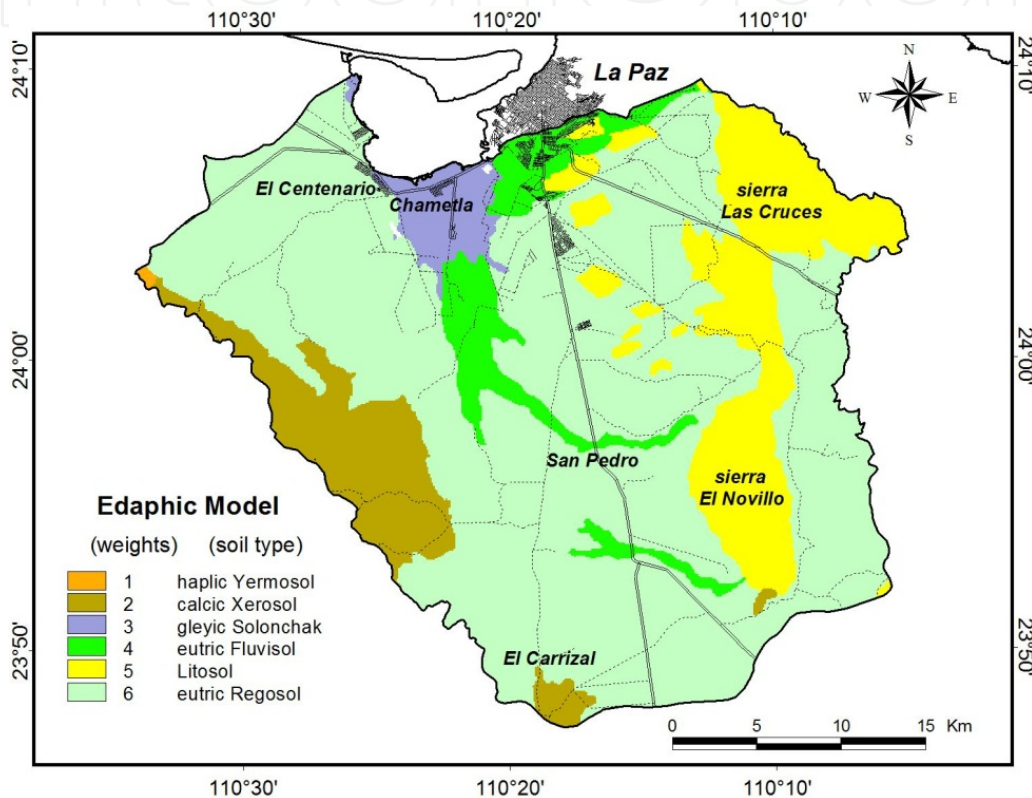
From Figure 7, is observed that most of the basin is characterized by regosol. Litosol extends Eastward, fluvisol at the middle, and xerosol to the West.

Due to the characteristics and properties of the models and the values assigned to their classes in relation to their contribution to groundwater recharge, it is observed that areas with better chance of recharge are located in plain areas, mainly alluvial. But if we assume that there is little rain in these areas, their contribution to recharge will not be the same. There for, it was necessary to include the parameter of rainfall, which is determinant in this process.

The precipitation model of the basin of La Paz (Figure 8) comes from Cruz-Falcón et al. (2011). It was generated from 25 year precipitation data (1980 to 2004), of 12 weather stations located within and outside the basin of La Paz, provided by the State National Water Com-

mission (Comisión Nacional del Agua, CNA). To obtain this model, it was calculated the total annual precipitation (TAP) for each climatological station, and TAP of 25 years was averaged. The average TAP for each station was interpolated to obtain isohyets, using spline method. Averaged TAP contours were rasterized with a 100 m spatial resolution.

According to the model, precipitation extends in a range from 150 to 400 mm/year, where most precipitation occurs in elevated areas located to the East and SSE of the basin, but decreases toward the opposite side (NNW).



**Figure 7.** Edaphic model of the basin of La Paz

### 3.3. Integration of models

The obtained models of terrain slope, geology, geomorphology, land use and vegetation, soil and precipitation were integrated to build a new model containing the areas (polygons) of potential rainfall recharge in the basin of La Paz (Figure 9). This model includes the distribution of polygons for seven classes, from a poor (1) to very good (7) groundwater recharge.

According to the obtained results, the recharge areas that resulted from the classes: moderate (5) to very good (7), may be considered as main recharge areas. Therefore, it is assumed that rainfall potential recharge areas in the basin of La Paz, are located on the East, South and Southeast of the basin, from sierra Las Cruces to sierra El Novillo, and the Northern portion of the valley of El Carrizal (Figure 9).

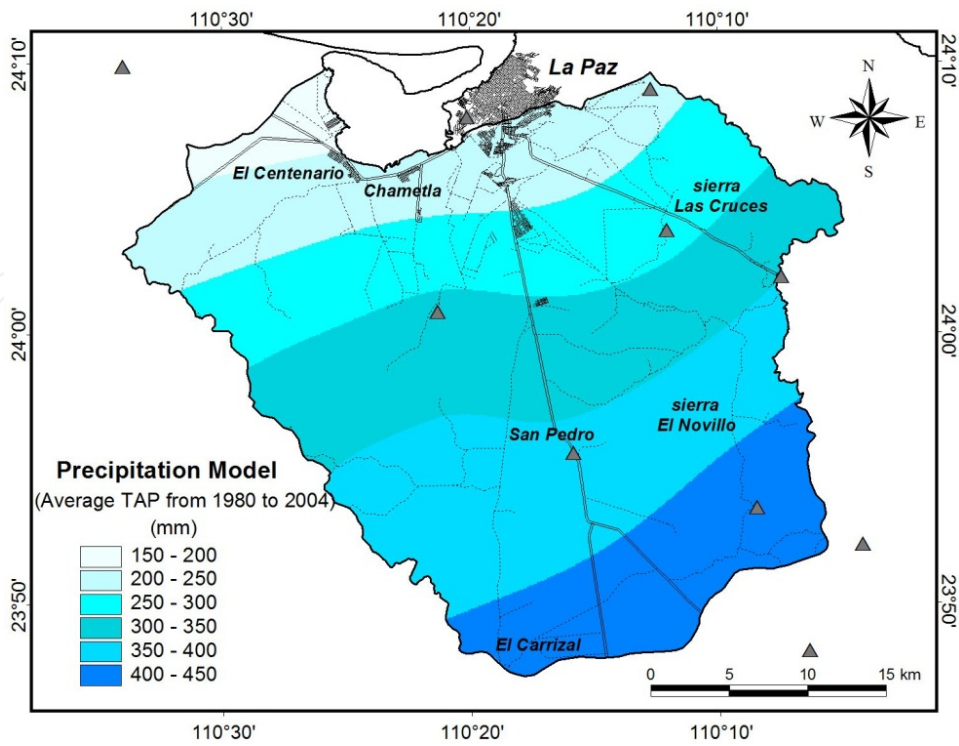


Figure 8. Precipitation model of the basin of La Paz. From Cruz-Falcón (2011).

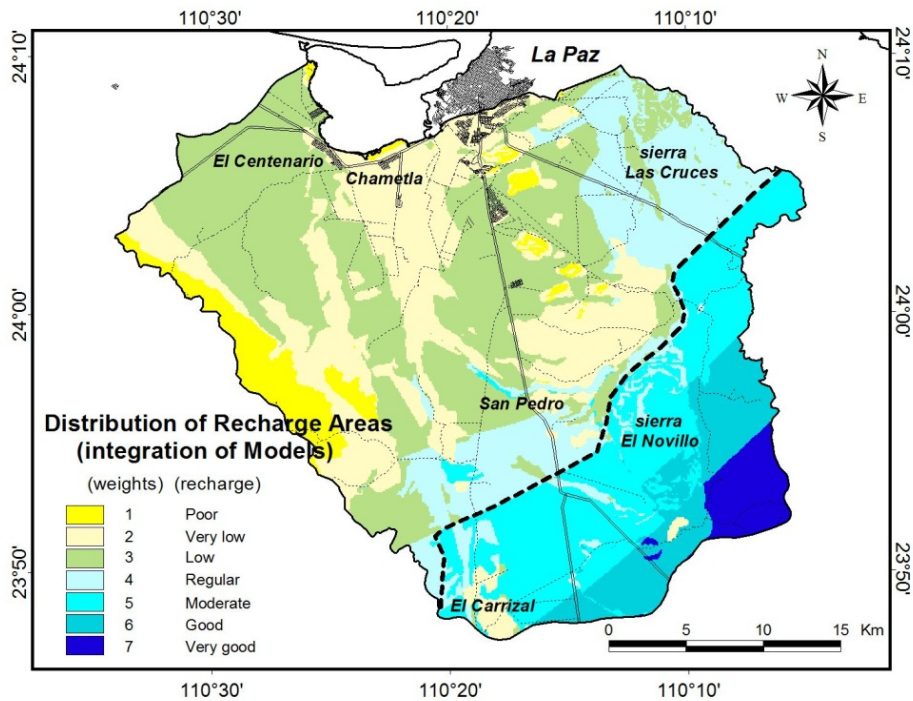


Figure 9. Model of rainfall recharge areas in the basin of La Paz. Dotted line delimits the best recharge areas (from moderate to very good).

## 4. Conclusions

The most important implications of the method of weights in the study of groundwater, enable to locate the rainfall recharge areas in the basin of La Paz. This includes spatial analysis and union of different layers, allowing to analyze and process each parameter in a simply and rapid way, by means of a geographical information system.

The use of the method of weights can handle the tendency or results based on the weight assigned to each class. For this study, the model of geology was given a higher weight to the fractured granite than to alluvium, due to authors criteria.

The final results of the processes involved with this method can be used, among other things, in watershed management, environmental management plans, urban development programs, and municipal strategic planning.

Due to the characteristics of the obtained models with its different classes, in relation to their contribution to recharge, it is observed that areas that best contribute to rainfall recharge are located on medium and high elevation zones within the basin. Poor, low and very low recharge areas, are distributed at the Center and Northwest of the basin, while regular recharge areas are distributed to the South and Northeast.

The areas classified from moderate to very good recharge, must be considered the best rainfall recharge areas of the basin of La Paz.

The best rainfall collecting areas, and rainfall recharge areas in the basin of La Paz, are located on the mountains and hills to the East and Southeast of the basin, around sierra El Novillo and Las Cruces, and the Northern portion of the valley of El Carrizal. Here, rainwater percolates underground within weathered igneous and metamorphic rocks, and through cracks and fractures. Then water is transported slowly down to the plains by groundwater flow. This process allows for recharge of the aquifer of La Paz, which is located in the valley.

At present, urban growth of the city of La Paz is not sustained on an ecological management program, neither on a sustainable urban development, that include ecological and economic alternatives for the preservation and conservation of the aquifer. In this sense, projected population growth of the city of La Paz towards the SSE of the basin, does not consider the natural rainfall collecting areas and recharge areas. Hence, it is very important and necessary to protect these areas, for being considered in land-use planning and urban development for the municipality of La Paz.

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