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Morphometric and vulnerability methods in the selection of landfill sites in active tectonic areas: Tangancícuaro valley, Michoacán, Mexico

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RESUMEN

La explosión demográfica, el desarrollo económico y el crecimiento de los grandes centros urbanos han tenido como consecuencia un incremento considerable de la producción de basura en el mundo. Su manejo y disposición final se encuentran en un punto crítico, siendo un asunto prioritario para respetar los requerimientos ambientales y de salud para la población. La falta de una metodología adecuada para la selección de sitios que reúnan condiciones de seguridad ambiental, sobre todo en campos volcánicos recientes y dinámicos, ha ocasionado la elección de sitios sumamente sensibles a la contaminación para la disposición de residuos sólidos municipales. Los requisitos de la normatividad mexicana vigente (NOM-083-ECOL 1996) quedan rebasados en la mayoría de los casos, debido a que no todos los elementos que se manejan se evalúan de una manera cuantitativa. En el presente trabajo se pretende demostrar la importancia, para la selección de sitios para rellenos sanitarios, de aplicar métodos enfocados a la evaluación de los niveles de vulnerabilidad de acuíferos (DRASTIC), incorporando a los mismos el uso de mapas morfométricos que reúnen los elementos de geología estructural, en regiones como el valle de Tangancícuaro, ubicado en la porción oriental del campo volcánico Michoacán-Guanajuato e influido por un ambiente tectónico activo representado por los grábenes de Chapala, Cotija y Penjamillo.

PALABRAS CLAVE: Vulnerabilidad, DRASTIC, campo volcánico, basurero, Michoacán, morfometría, fracturamiento.

ABSTRACT

Handling and disposal of garbage is a high-priority matter everywhere. The requirements of the Mexican standards for drinking water (NOM-083-ECOL-1996) have been exceeded in most cases. For an adequate site selection, this paper shows the importance of applying methods for on the evaluation of vulnerability levels of aquifers (DRASTIC), incorporating the use of morphometric maps of structural geology, in regions such as the Tangancícuaro valley, in the Michoacán-Guanajuato volcanic field and influenced by an active tectonic environment represented by the grabens of Chapala, Cotija and Penjamillo.

KEY WORDS: Vulnerability, DRASTIC, volcanic field, landfill, Michoacán, morphometry, fracturing.

INTRODUCTION

This work describes the results of a geo-hydrologic study focused in the selection of a site that can be used as a landfill in the Tangancícuaro valley, to comply with adequate operability conditions for preserving the environment; in other words, taking care that the landfill will not become an environmental, social and health problem for the area.

The area under study, known as the lake of Camécuaro National Park, is located to the northwest of the Michoacán state, between the coordinates 19º 53' 00" and 19º 54' 00" north latitude, and 102º 13' 00" and 102º 14' 00" west longitudes, in the municipality of Tangancícuaro, with an approximate surface of nine hectares (Figure 1).

Camécuaro lake is located in the Tangancícuaro valley, which is one of the more important national parks in northwestern Michoacán state (Figure 1).

The presence of this park adds a limitation in considering the location of the landfill. Its origin is related to the circulation of waters in the Mexican Volcanic Belt, which is associated to a monogenetic volcanoes-type shield, characterized by the existence of leafy and old Ahuehuete trees that surround a lake of 7 m average depth. This water body owes its existence to a large number of springs that converge in it.

The flow of such springs has recently diminished in a drastic way, many of them being drought up, an alarming situation for it endangers the very existence of the park, whose main attraction is in fact its lake, as well as the flora and fauna that coexists around and in it. The appropriate location of the landfill is therefore important for the preservation of the park and its environment.

The objective of the present work is the assessment of sites for landfills through the application of morphometric (general and horizontal dissection of relief), and vulnerabil-

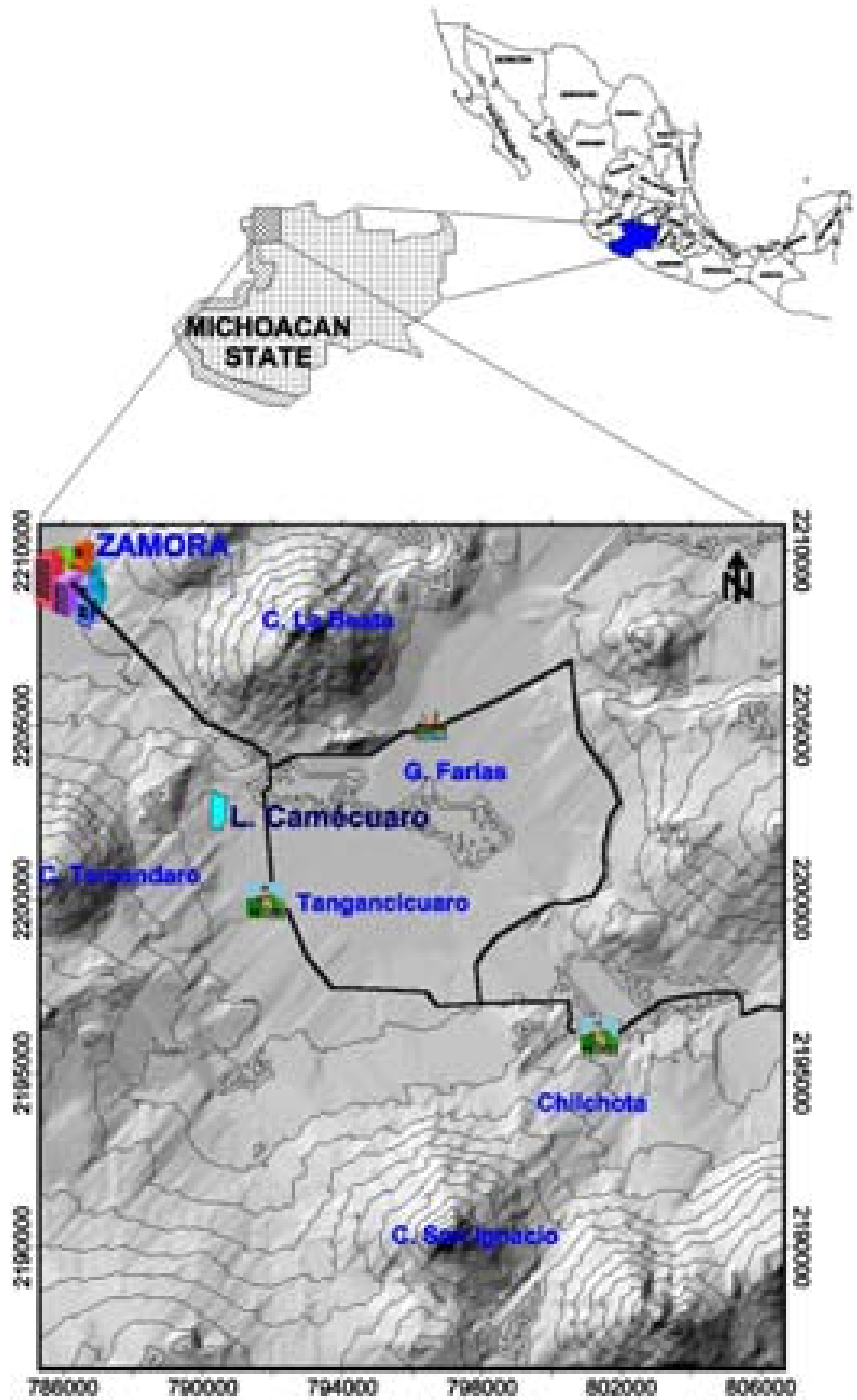

Fig. 1. Location of Tangancícuaro valley, Michoacán state.

ity methods with normalized DRASTIC in a volcano-sedimentary tectonic active environment.

GEOLOGIC SETTING

The area under study is located in the western sector of the Mexican Volcanic Belt (MVB). It is one of the outstanding magmatic counties in Mexico, and it is characterized to be an extended area with the shape of an arch (Figure 2).

One of the most remarkable features in the western portion of the MVB is the presence of a system of three rifts that are intercepted in a continental triple point (Dickinson and Snyder, 1979) located 50 km southwest of Guadalajara city.

The distribution of the volcanic and tectonic elements has the following preferential orientations-E-W (Chapala System), NE-SW (Zacoalco System), and N-S (Colima and Penjamillo Systems).

The regional stratigraphy present in the region of Arandas-Atotonilco and Villa Chavinda (Pasquare and Zanchi, 1985), recognizes the Intermediate Volcanic Sequence (IVS) of the lower Miocene (12 to 8 m.y.) as the oldest unit.

Volcanic activity (Pleistocene, 1.3-0.83 m.y.) is broadly distributed in the region (Garduño *et al*., 1999), possibly starting with short andesite -basaltic phases that evolved later into hiperstena basalts, forming lava cones and small volcano shields as La Beata, Tamandaro, and San Ignacio, which could be associated to well-known volcanic prominences such as the Encinal and Nogales volcanoes, and those that constitute the high parts of the Sierra de Pajacuaran (Figure 3).

Quaternary volcanism corresponds to the most recent volcanic events in the region, represented by cineritic cones distributed in the area, whose volcanic products are mainly olivine basalts and andesites, being the radiometric age reported for these rocks of 0.5-0 m.y. (Pleistocene to half-Holocene) in the towns of La Cantera, La Ladera and Colorado (Garduño *et al*., 1999).

The most recent lithological unit is represented by the recent superficial deposits of the volcano-sedimentary and alluvial types, whose grains vary from clays to rounded gravels, forming the wide valleys of Zamora and Tangancícuaro (Figure 3).

STRUCTURAL GEOLOGY

The structural analysis of the area was done with the aid of aerial photographs, topographical charts, geologic maps, and field verifications. For the purpose of this work, the area under study was divided in four zones (Figures 1 and 3):

Zone 1 is located in the northwest of the area. It includes the Beata, and Tamándaro hills. The prevailing fracturing systems are oriented NE40°SW, and NW15°SE. Smaller systems correspond to the orientations N-S and E-W (Figures 1 and 3).

Zone 2 is located to the northeast of the Camécuaro lake. Curiane and San Antonio are its main hills. The prevailing fracturing system runs E-W, while other smaller systems show an NE-SW orientation (Figures1 and 3).

Zone 3 is located in the southwest of the area under study; there are some hills of low elevation, the NE10°SW fracturing system prevails, while other smaller systems are the NE35°SW, NW35°SE and N-S (Figures1 and 3).

Zone 4 corresponds to the southwest of the Camécuaro lake. In this area, the San Ignacio hill is located. The system that prevails is the NW35°SE, and other smaller systems have orientations N-S and NW15°SE (Figures1 and 3).

In the area as a whole, the predominant fracturing systems are N-S, NW15°SE, NE45°SW, and in smaller grade the regional system appears E-W of the Chapala graben. The radial drainage in the volcanic apparatuses is characteristic of the region.

In adjacent regions, the alignments of important dimensions and with preferential orientation E-W are prevalent. A good example of this type of structural system is the Llano Grande fault, one of the most spectacular in the area, and whose descriptive characteristics are very similar to the Pajacuaran fault, also of a normal type, with regional orientation E-W, that spreads towards the W-SW, with plane of inclination 60° to the N, conforming escarps that can reach a topographical difference of 200 m within a 14 km distance (Figures 2 and 3).

METODOLOGY

Several methods of field and cabinet work were applied for the present investigation. Sixteen samples of wells and springs water were obtained for their chemical analysis. During its sampling, temperature, electric conductivity, dissolved total solids, and pH data were recorded.

The DRASTIC method (Aller *et al*., 1985) was used for quantifying the vulnerability index of the aquifer in the valley. According to this method, vulnerability is determined by assigning a numeric hierarchical outline to the param-

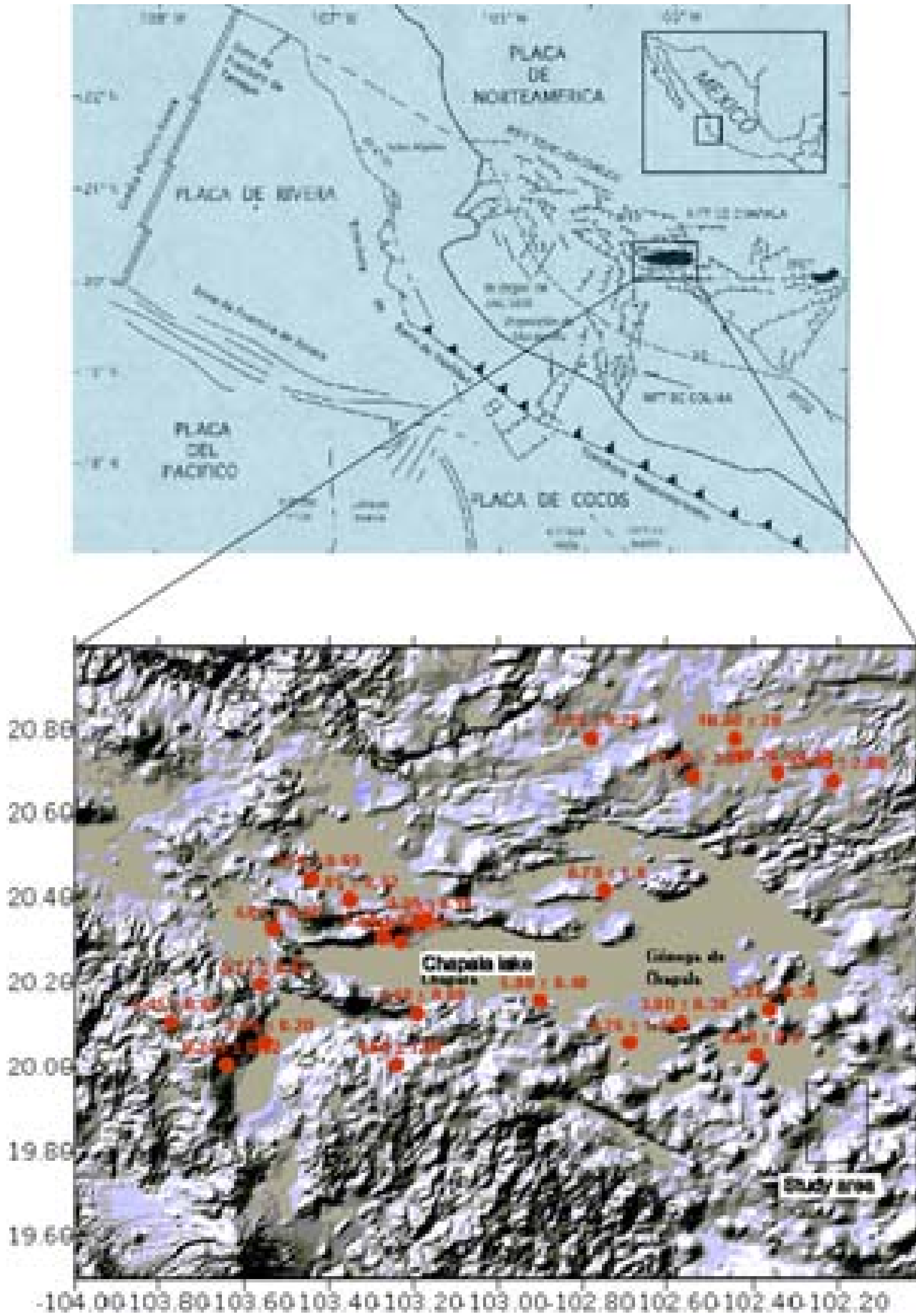

Fig. 2. Tectonics of Chapala Lake.

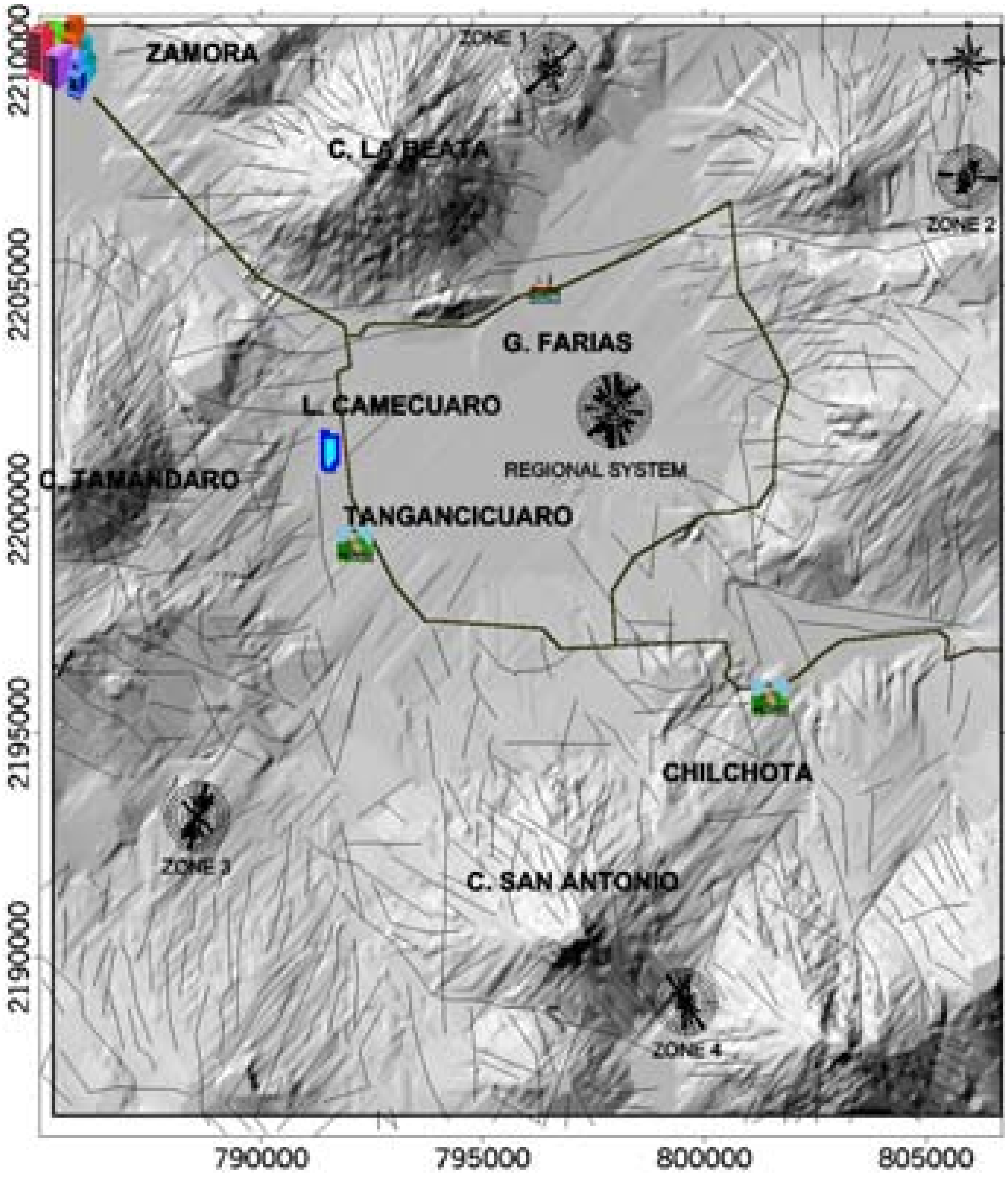

Fig. 3. Geology and structural geology of Tangancícuaro valley.

eters represented by the acronym DRASTIC—Depth to water table; net recharge; aquifer media; type of soil; topography; impact of the unsaturated zone, and hydraulic conductivity.

Each factor was previously normalized to a scale from 1 to 10. Once assigned to a range, the values were multiplied by a respective weight (P), which numerically represents the importance and influence that each factor has in the handling of the groundwater, being 5 the most relevant, and 1 the one of lesser impact. Finally, the vulnerability plane was normalized to a scale from 0 to 100 units.

In order to determine those potential areas of recharge of the aquifer in a fractured media, or those areas whose hydrodynamic role would be of discharge of the aquifer, in the case of the valley of Tangancícuaro, two morphometric methods were applied: Density of Dissection of the Relief (DDR) and General Dissection of the Relief (GDR).

HYDROCHEMISTRY

Most of the bore wells and springs from the basaltic aquifers are classified as Ca^{2+}-HCO_3- type and Ca^{2+}-Mg^{2+}-HCO_3- type. Because of the similar in lithology and chemical character, the Ca^{2+}-Mg^{2+}-HCO_3- waters probably reflect deposits of the type volcano-sedimentary and basalt weathering. The predominance of Mg^{2+} and Ca^{2+} in some samples probably reflects the influence of ferromagnesian minerals such as olivine and plagioclases.

In the study area, the smaller values of Total Dissolved Solids (TDS) are present in the mountainous areas (160 mg/L), increasing towards the exit of the hydrological basin of Tangancícuaro (400 mg/L), in the Adjuntas region (Figure 4).

The TDS contours trend to increase in a preferential way towards the northwest of the area. The Camécuaro lake represents a discharge area, with values of 320 mg/L. This trend is similar in chloride concentration and it is indicates that the flow is in that direction. The chloride concentration is about 8 mg/L, and it is suggested that this concentration derived from the local recharge.

HYDRODYNAMIC BEHAVIOR

In accordance with the geologic and hydrogeological characteristics of the different units, the possible model of the hydrodynamic operation settles down in the valley of Tangancícuaro.

Some factors that influence the process of recharge of the aquifer in the valley have been defined. A first factor is the contribution of the infiltrations of the precipitations through the preferential areas of recharge, being in this case the whole mountainous relief that surrounds and defines the valley, notably the La Beata hill, in the north portion, and the volcanic altitudes located to the south and southeast, such as the La Cruz, San Ignacio, Curiane, and San Antonio hills. Its circulation is relatively fast since it is given through a fractured medium of high permeability, to flow later trough formations of variable porosity.

Although there is a superficial layer that limits the direct hydraulic communication of the surface towards the aquifer on the valley, possible contributions from the pluvial precipitation and watering return are not discarded. Lateral discontinuities of the loamy packages could allow the flow towards the aquifer. The discharge is carried out by means of different depth and shallow wells for water extraction, treadmills and springs through almost 100 hydraulics works prevailing wells with depths equal to or smaller than 100 m.

The preferential direction of the flow is SW-NW (Figure 5). The recharge has components in other directions, according to the zone. Some regional structures (such as the Llano Grande fault) work as preferential conducts communicating regional flows of thermal waters with local flows of waters with cooler temperatures, as in wells such as the one in San Antonio Ocampo and Gómez Farías.

MORPHOMETRY

The Density of Dissection of the Relief (DDR), also called horizontal dissection of the relief in plane, represents the erosion of the terrestrial surface as for the longitude of the thalweg for km^2. In a volcanic field as the Michoacano, one of the most important factors that intervene is the fracture status, and its importance resides in the fact that the fractures constitute areas of weakness, which help to conduct the water and, in consequence, the dissection of the relief.

In a general hypothetical way, we could say that the values would tend to be higher in mountain areas with fractured rocks and, in the same way, the opposite situation would help to obtain reduced values. In our case, as observed in Figure 6, value ranges from 1.0 to 2.8 km/km^2 were obtained.

In the case of the General Dissection of the Relief (GDR) method, it is sought to quantify the contrast of the relief. This is the dissection of the profile in plane. The method consists on measuring the longitude of the level curves in a given area—in our case of 16 km^2—and estab-

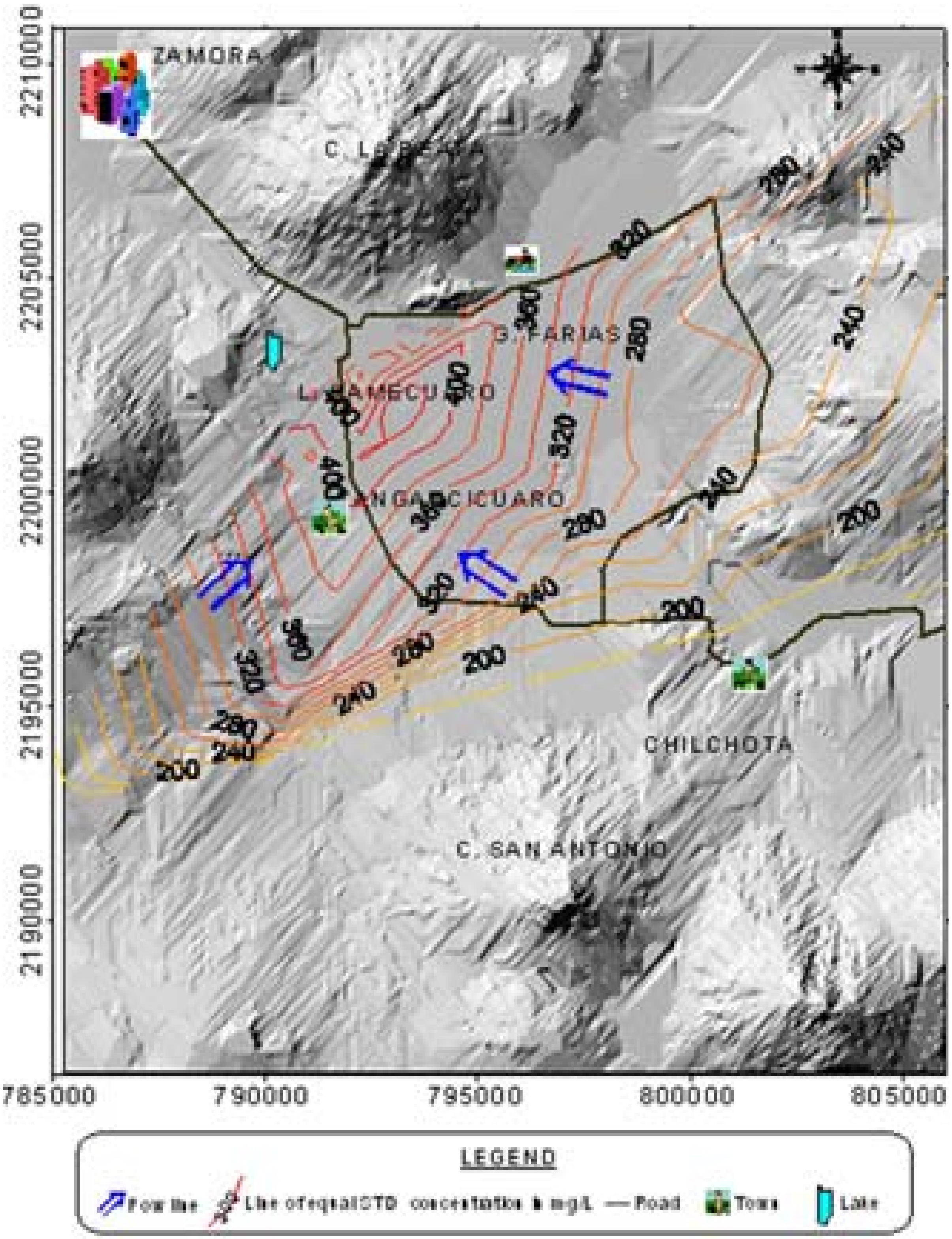

Fig. 4. Distribution of TDS in Tangancícuaro valley.

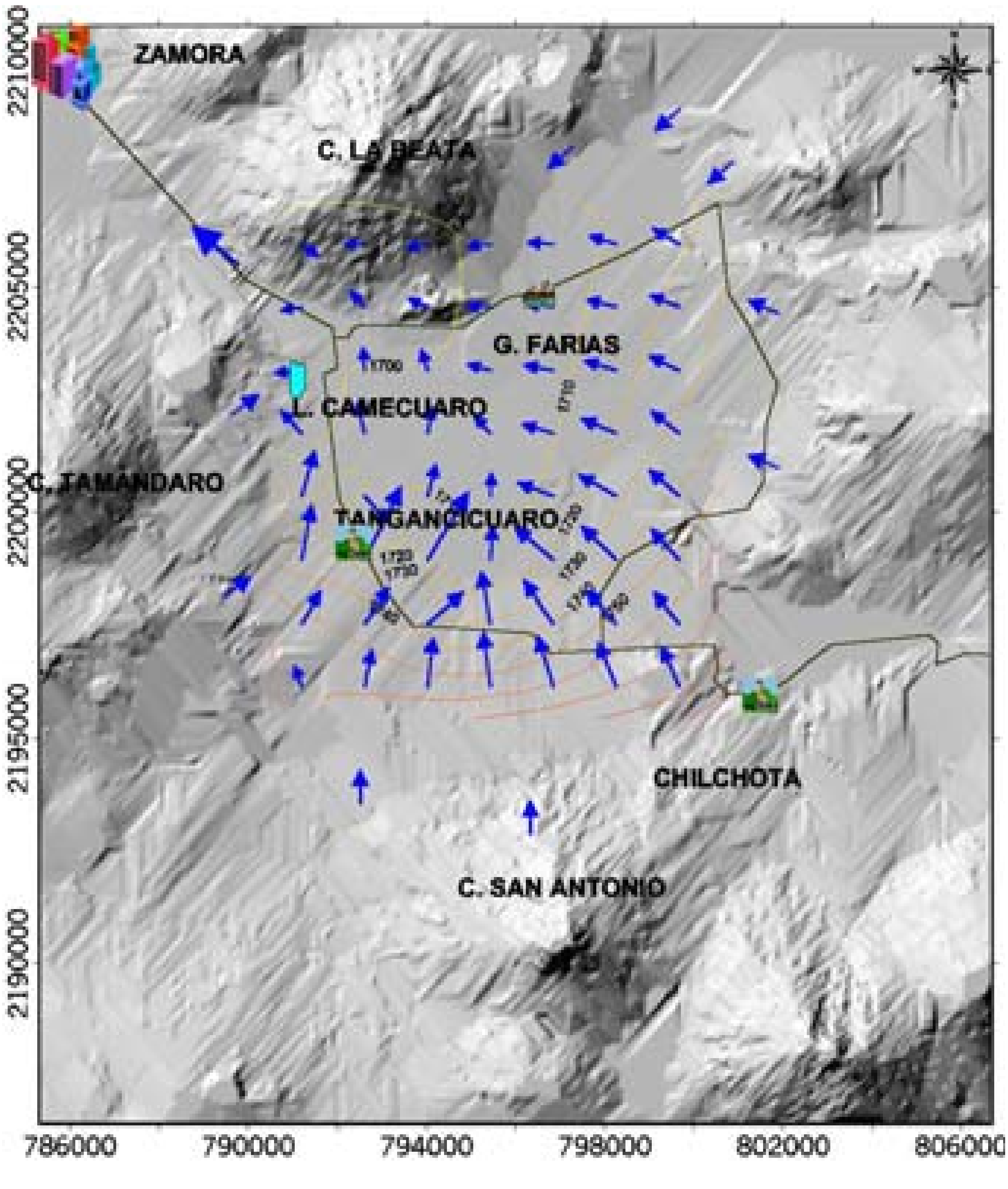

Fig. 5. Direction of groundwater flow in Tangancícuaro valley.

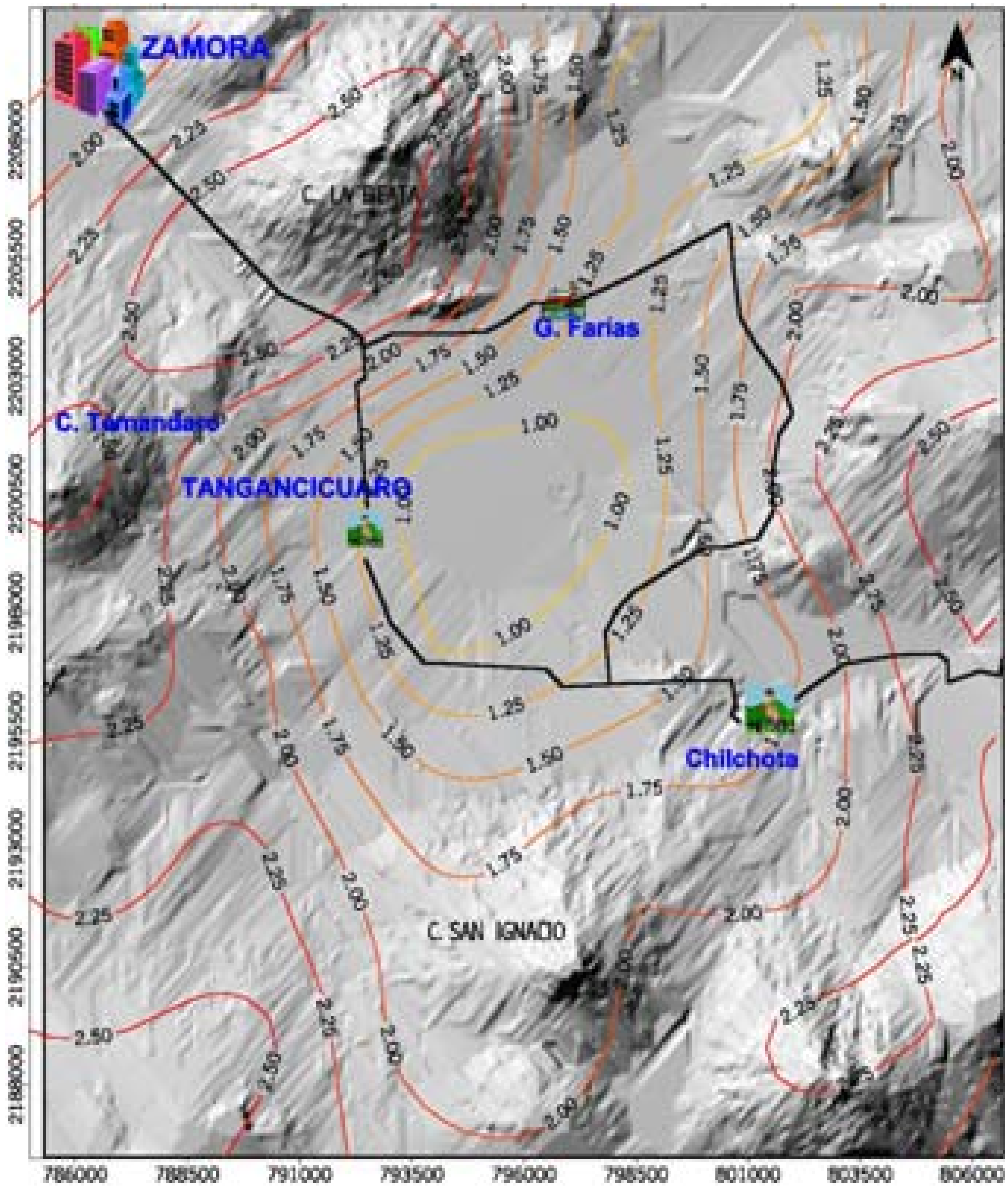

Fig. 6. Distribution of the Density of Dissection of the Relief (DDR) in Tangancícuaro valley.

lishing its relationship in terms of km/km^2. Only 100 m distance level curves were included in the measurement, giving values of 0.1 to 3.1 km/km^2, with the Cerro Viejo and Curiane hills, located to the southeast and east, respectively, highlighted as those of highest erosion grades. The lowest ranges (0.2-1.0) belong to the areas of smaller slopes. It can be inferred that the highest values differentiate areas in which erosive processes are more important than the accumulative ones, as long as the minimum values correspond to areas where the accumulative processes prevail, as in the Camécuaro lake.

VULNERABILITY WITH NORMALIZED DRASTIC

Since the DRASTIC vulnerability plan is the result of the arithmetic sum of the seven parameters mentioned above, its high values are caused by high values of each one of them. In Figure 7, the lowest values (0-10) are located in the Tangancícuaro valley, and the highest values (90-100) are located towards what has been considered the recharge area, and in the vicinities of some permeable structures such as geologic faults. In the case of the Camécuaro lake, of special interest and reason for the application of this methodology, the registered values are between the range of 60-70, this is because it belongs together with the considered area of discharge of the hydrological basin, and the springs that give origin to this lake are in fractured basalts and their origin could be associated with some of the regional structures.

DISCUSSION AND CONCLUSIONS

The regional flow of the groundwater has a preferential pattern towards the NW, as was shown by the piezometric and hydrogeochemical behavior (Figures 4 and 5).

The La Cruz hill is of special importance in the recharge of the springs of Camécuaro, and actions guided to their ecological protection must be taken.

Although the DRASTIC method considers topography as a parameter that influences very little in the vulnerability of the aquifer, the topographical slope is indeed a factor that influences the superficial runoff of water, and that has not been considered in the erosive process to the terrestrial relief, which would be very useful in the location of landfills.

The application of the different morphometric methods allowed the identification of morphological areas associated with potential areas of recharge of the aquifer, which correspond to the main prominences of the region, with a high fracturing grade. Areas were identified where the erosive processes are more important than the accumulative ones; these areas correspond to regions with the highest values of dissection density and general dissection of the relief, which can contribute in taking the proper decisions for the location of landfill, due to the fact that it should be located in areas with little risk of erosion. Other areas with lower values of these morphometric parameters are considered to show erosive effects of smaller incidence in the erosion of the solid residuals that are managed in the landfill.

In another valley in the Michoacán state, at Zamora (Silva *et al.*, 1998a, 1999; Ramos, 2002), morphometric maps (general dissection of relief and density of limits) have been used to reinforce the location of landfills determined through DRASTIC vulnerability maps, since this method alone does not consider highly erosive and fractured scenarios.

As for vulnerability, this is higher in mountainous areas with fractured rocks in the surroundings of the valley (Figure 7).

The areas were identified with the normalized vulnerability map, with smaller risk of contamination to the aquifer. The internal parts of the basin with values lower than 40 can be considered as acceptable for the location of landfills; such areas greatly match with the ones identified ones through the proposed morphometric methods. Values higher than 50, similar to the morphometric ones, belong to very vulnerable areas, since they correspond to recharge areas with high fracturing grade (Figures 5, 6 and 7).

Although most internal parts of the basin show good morphometric and vulnerability values for the location of a landfill, the use of such areas is restricted by its land use, which would affect protected natural parks, human populations, and important cultivation areas.

Considering the flow patterns, the recharge and discharges areas, the location of populations, cultivation areas, protected areas, as well as morphometric and vulnerability indexes, two main areas were defined for the location of the landfill. The first one is located to the east of the Gómez Farías town, with a morphometric index of 1.5 to 2, and vulnerability of 30 to 40. The second area is located to the south of Tangancícuaro, with registered morphometric index from 1.25 to 2, and vulnerability from 20 to 50 (Figures 6 and 7).

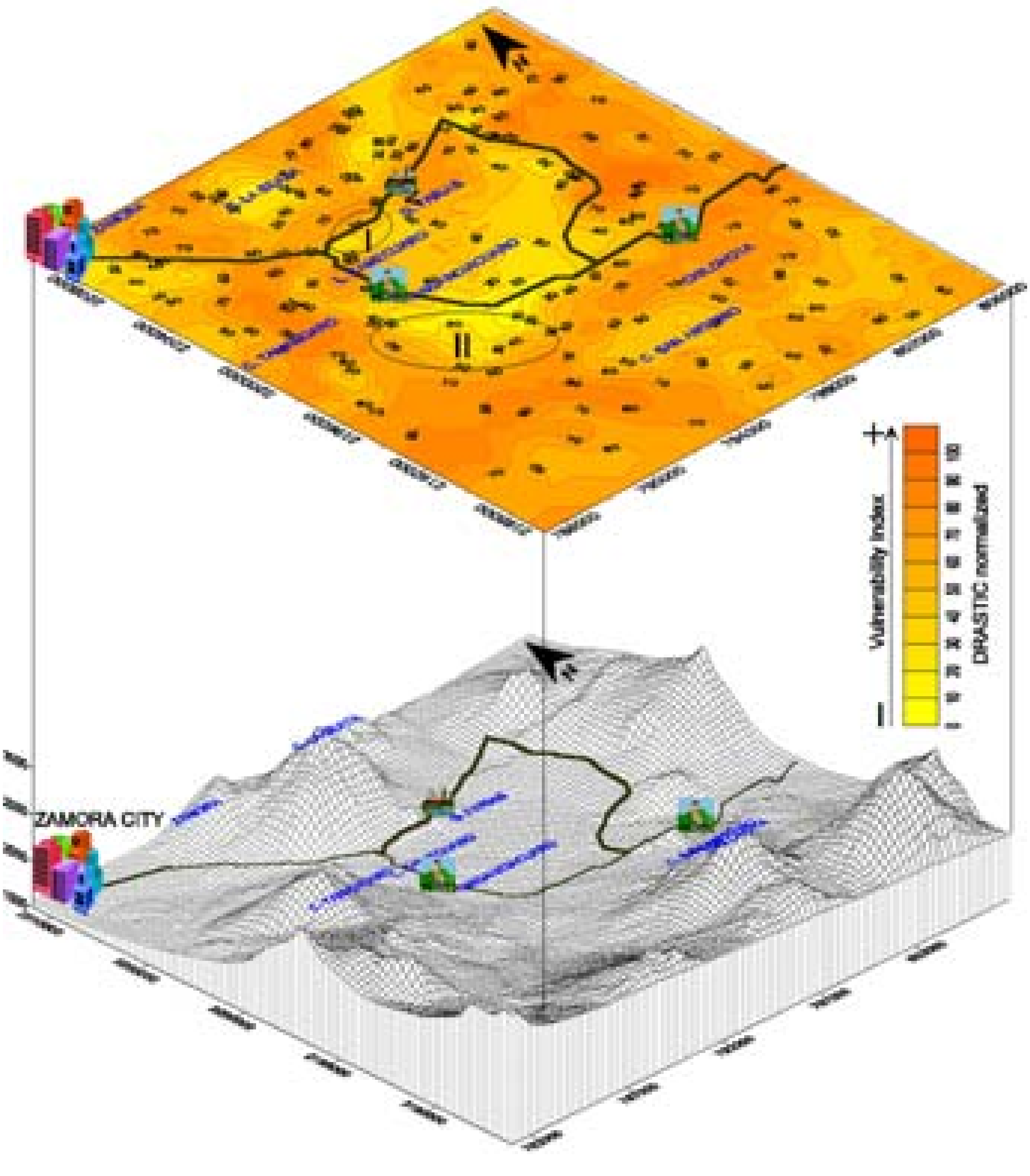

Fig. 7. Model of normalized vulnerability DRASTIC in Tangancícuaro valley.

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