Chapter 18

# A Geologic and Geomorphologic Analysis of the Zacatecas and Guadalupe Quadrangles in Order to Define Hazardous Zones Associated with the Erosion Processes

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Additional information is available at the end of the chapter

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## 1. Introduction

In the State of Zacatecas, Mexico (**Figure 1**), the environment is not usually taken into account as a critical variable for the urban growth and development planning. The expansion of the cities of Zacatecas and Guadalupe in the study area is merely based on the land use change according to the Urban Development Code[1] and the Urban Development Plan 2004-2030 [2]. The Code states the urban growth policies which apply to the whole state; whereas the Plan is a compilation of documents related to the urban growth tendency, population distribution, and basic population services (i.e. water supply). Regardless of the scale, the criteria for the land use change policies are unclear. The Urban Development Plan [2] suggests avoiding urban growth towards areas geologically and topographically unstable and those with flood potential. In every case, the slope should be less than 30°. There are no available maps that indicate where these areas are located, so the criteria for land use will remain unclear.

Although the geology and geomorphology are mentioned [2], their value as critical variables is not taken into account in practice for any purpose. The geologic and geomorphologic variables defined [3] are only indicated, but not located on a map for planning development. Moreover, it is suggested [2] that there is a necessity for a detailed mapping of the geomorphic agents defined [3].

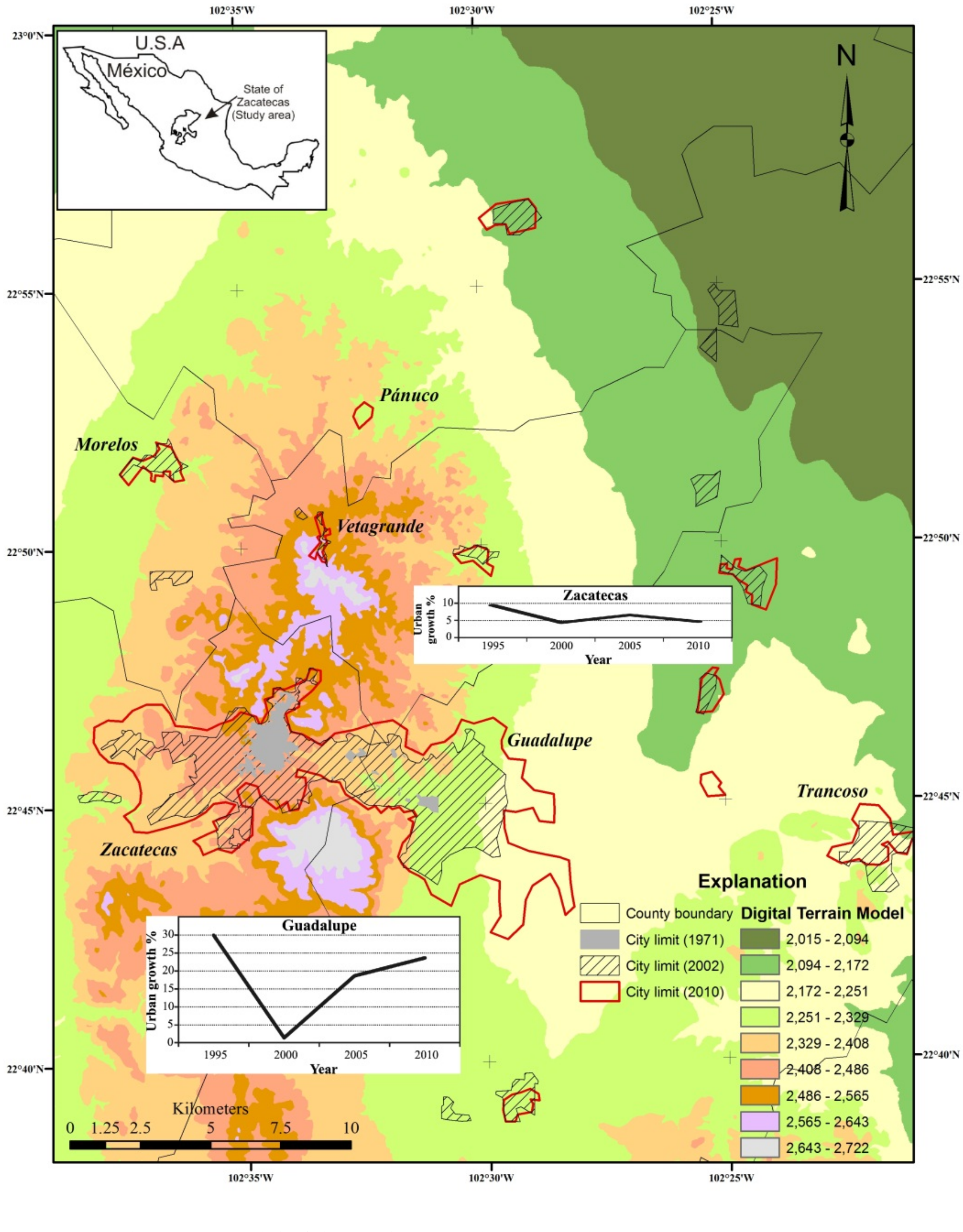


**Figure 1.** Digital Terrain Model of the study area. The area includes six municipalities whose names are in bold-italic. The largest cities are Zacatecas and Guadalupe. The graphs show the population growth during the last 20 years [8-10], Guadalupe is among the fastest growing municipalities in Mexico (~25% in 2010). The 1971 city limit was obtained from INEGI [11-12]; the growth of these cities until 2002 is a compilation made by the first author; while for 2010 it was a combination between a Google Earth image (August 5th, 2009) and field work. Inset is the location of the State of Zacatecas and the study area.

Due to the land use change and the subsequent landscape modification, the erosion processes are currently becoming active in places usually considered to be stable. The effects are: fractured streets, roads, and houses, voids under the streets and buildings, slope instability, and rock blocks falling next to the roads themselves (**Figure 2**). The primary erosion agent is rainwater. The geomorphic processes are slow but steady contributors, due to the semiarid climatic conditions [3]. The average annual precipitation is 500 mm/yr; while the average annual temperature is 22°C. Therefore, the erosion processes develop slowly, but successfully. Until now, the hazardous zones have only been reported in specific places; the effects of which are the mass removal under houses or streets with active fracturing and, in worst case situations, their slow collapse (**Figure 2**). The exact location of these areas has not been taken into account as a social, economic or environmental problem. The natural hazards recognized by the authorities are mostly related to the mining industry and their products (i.e. mine tailings, open pits); on the other hand, the erosion and its effects [2] are considered of minor importance. The landscape, geology, land use, soil cover, and their modifications are barely considered to be serious enough to promote the development of dangerous areas once the original conditions are changed.


**Figure 2.** Images showing the erosion hazards associated with different lithology: a) and b) are in the granitic facies of the Zacatecas Conglomerate; c) moderately consolidated facies of the Conglomerate; and d) deformed lava flows from Las Pilas Complex. Yellow arrows point toward the first attempt of damage repair. Purple arrows are the sites where a second repair phase has been attempted; while the green arrow shows a third repair phase. The red arrows point to the voids created due to the soil removal by the erosion processes.

For several years now, attempts have been made in order to identify and describe the geomorphic processes acting in the Zacatecas and Guadalupe cities and their relationship with geology and geomorphology [3-7]. In this paper we define the hazardous zones by means of a GIS analysis that integrates the geologic and geomorphologic mapping combined with the digital slope modeling, land use, and soil type.

## 1.1. Local geology overview

The stratigraphic sequence of the study area is composed by units ranging from the Early Cretaceous Period to Present Age (**Figure 3**). The oldest unit is the Early Cretaceous Zacatecas Formation[13]. The Zacatecas Formation is made up by Greenschists Facies metamorphic rocks whose protoliths are wacke, mudstone, limestone, as well as, interstratified conglomerates with lava flows and tuffs. The whole sequence is cut by dikes, sills, and dioritic laccoliths. Its upper contact is transitional with the Early Cretaceous Las Pilas Complex. This unit is composed of mafic lavas with pillowed and massive structure, commonly foliated and deformed (**Figure 4a and b**). Lava flows contain interbedded wacke, greywacke, mudstone, and minor tuff and limestone. It is considered that laccoliths and dikes of the Las Pilas Complex are part of the same volcanic sequence. Moderate to intense hydrothermal alteration affects the entire Mesozoic record. Both, the Zacatecas Formation and the Las Pilas Complex are known as the Zacatecas Group. This group shows the results of a Late Cretaceous compressive deformation stage and at least five extensional deformation phases that have occurred from the Oligocene to Recent [16]. The association of deformed structures with faulting and steep slopes promotes rock falling.

The Las Pilas Complex is unconformably covered by the Eocene Zacatecas Conglomerate that crops out in the Zacatecas and Guadalupe cities. This conglomerate is composed of five facies named according to their clast-rich abundance and their physical characteristics (**Figure 4c and d**). The sandstone-rich layers are more easily erodible than the conglomeratic ones. This characteristic promotes differential erosion processes that, in combination with moderate to steep slopes, favors the generation of hazardous areas. The conglomerate was deposited in a WNW-ESE fault-bounded basin whose deformation is less intense than the one showed by the Zacatecas Group.

At the top of the stratigraphic column the Zacatecas Conglomerate is in transitional contact with the Oligocene-Miocene Volcanic Sequence that is composed of interbedded ash-flow and air-fall tuffs, breccias, and rhyolitic flows and domes [3, 17]. They commonly develop cliffs that, when associated with steep slopes, encourage the falling of the rocks. The cliffs next to the main faults and steep slopes are also suitable areas for the rock falling process to happen.

## 1.2. Geomorphic features and unconsolidated deposits

The study area belongs to the Basin and Range extensional province [16] that is formed by NNW-SSE normal faults forming horsts and grabens. The main geomorphologic feature is the Sierra de Zacatecas that is oriented NNW-SSE (**Figure 5**) bounded to the west by the

Calera Valley and to the east by the El Palmar Valley. A minor range, Sierra de Tolosa, is located to the east; both ranges are separated by the El Palmar Valley.

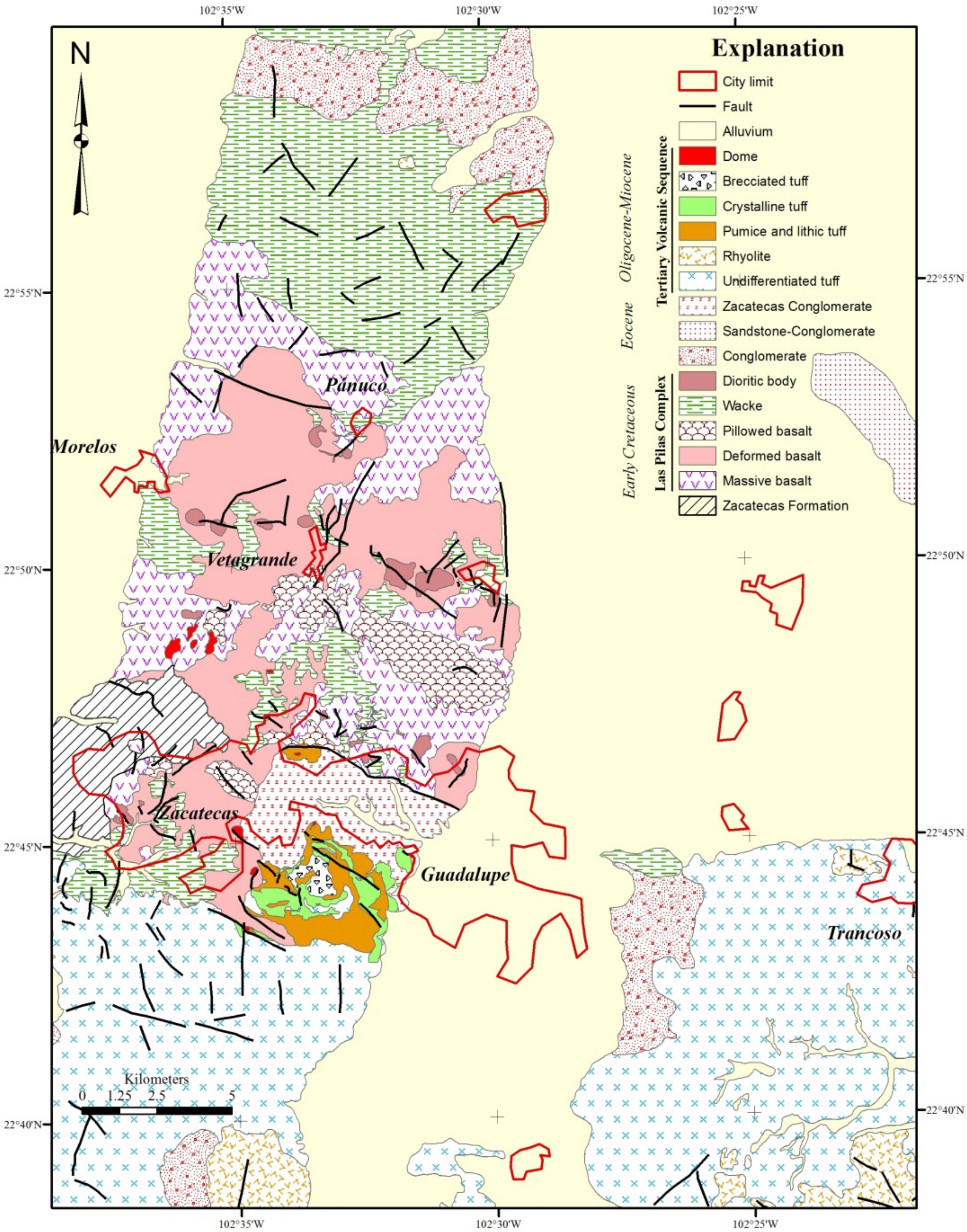


**Figure 3.** Geologic map of the Zacatecas and Guadalupe quadrangles. Detailed mapping from the Mesozoic sequence is taken from [13-14], while the Tertiary Volcanic Sequence is from [3, 15]. The names are from the municipalities of the study area.

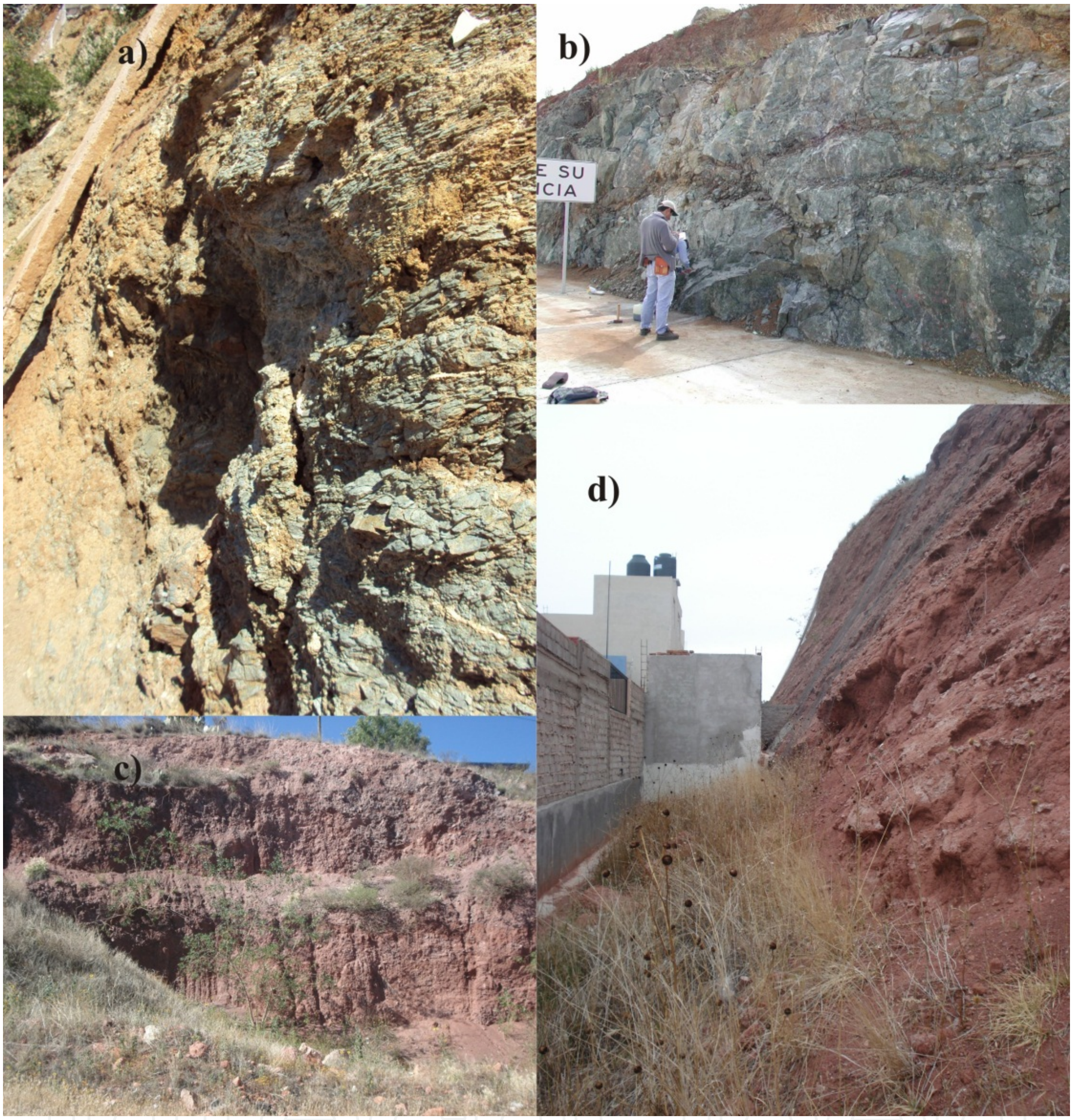


**Figure 4.** Images showing the main physical characteristics of lithological units that crop out in the Zacatecas and Guadalupe quadrangles. The Las Pilas Complex can be deformed (a) or massive (b), while the Zacatecas Conglomerate can be moderately consolidated (c) with differential erosion (d).

The main erosional agent in the area is rainwater; it affects unconsolidated to moderately consolidated sediments either from slope or fluvial deposits, as well as alluvial fans. These geomorphic features occur in the neighborhood of the present city limit (**Figure 5**). The slope deposits are made of interbedded sandstone and conglomerate. The sandstone thickness is less than 50 cm, whereas the conglomerate thickness varies from a few centimeters up to 30 meters. Commonly, both show normal gradation and, sometimes there are interbedded pumice and/or lithic tuffs. Since the sandstone more easily eroded than the conglomerate, it generates a differential erosion process (**Figure 4d**).

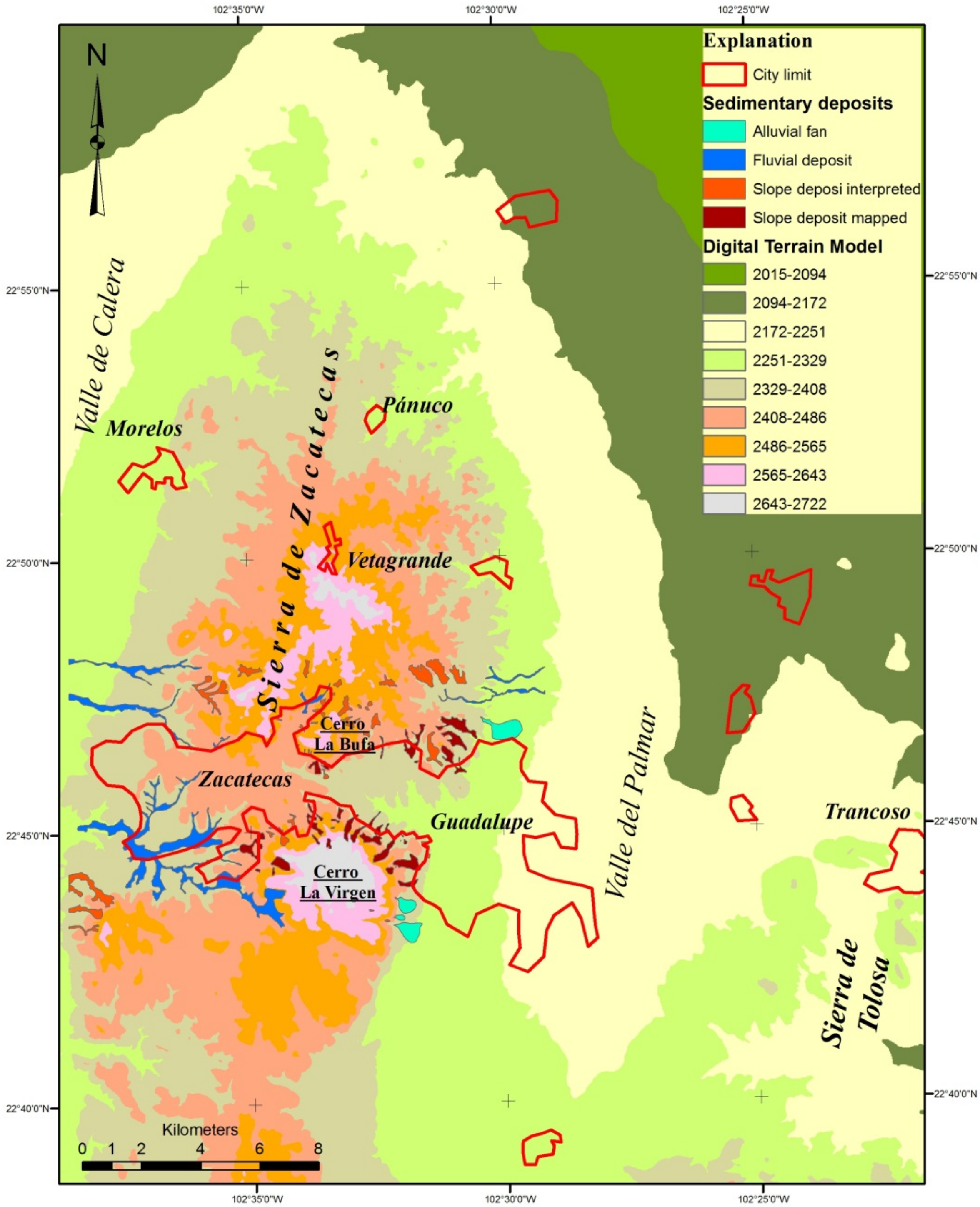


**Figure 5.** Digital Terrain Model showing sedimentary deposits that are in the neighborhood of the city limit of Zacatecas and Guadalupe. Horizontal bold-italics names are the municipalities; while in italics are the ranges and valleys. The main topographic features are underlined.

The slope deposits are of unknown age. Their morphologic expression is masked by the relief. The cities of Zacatecas and Guadalupe are currently growing directly on these deposits (**Figure 5).** Regarding the alluvial fans, there are a few of them in the eastern side of the Sierra de Zacatecas because most of the valleys are used for agricultural activities. The fluvial deposits are common in the western side of this sierra; however, the arroyos are currently modified due to city growth.

The buildings constructed on moderate to loosely consolidated sediments and lithological units are more vulnerable than those with well consolidated materials. In the sedimentary deposits shown in **Figure 5** the erosion of loose materials generate hazardous zones if the terrain slope is over 20°.

## 1.3. Land use and vegetation

The study area is located in a semi-desertic area with an average annual precipitation of less than ~500 mm/yr so most of the water supply for any all human activities is taken from underground wells. In these conditions the vegetation varieties are limited (**Figure 6**). The valleys are mostly used for agriculture. The thorn scrub and nopal (*Opuntia*) occupy the gentle hills of the sierras de Zacatecas and Tolosa. This type of vegetation requires little water and their roots extend laterally. The bushes are either natural vegetation outside the city limit or reforested areas inside those limits.

Since the original data was generated during the decade of 1970 [18-19], the situation now is different. The area shown as "Natural bushes" (**Figure 6**) is currently being substituted by thorn scrub and nopal. However, there is no up-to-date cartography.

The land use shown in **Figure 7** is taken from [18-19]; as well as in **Figure 6**, the valleys are used for agriculture. Cattle use is now greater, while the forestry area has decreased. Though the information on the criteria used to define "forestry use" is unclear, informally, these areas were considered for land conservation. However, since there are no written rules, the land use changes and modifications are based on unknown criteria. What has been seen is a continuous modification of landscape for urban purposes next to the city limit.

The land use map (**Figure 7**) was created from the INEGI (Instituto Nacional de Estadística, Geografía e Informática), institution depository of most of the cartographic information in the country. These maps are the basis for all the projects that require cartography. This being said, the conditions of the maps vary. The older ones were made different than the ones made today.

## 1.4. Edaphology

The soil classification used here is that of the United Nations Educational, Scientific and Cultural Organization [20]. In the Sierra de Zacatecas, where most municipalities are located, the Lithosol Eutric is dominant (**Figure 8**). It is composed by local, scarcely transported, rock clasts whose size varies from coarse sand to gravel; usually it is poor in organic matter. Its thickness is less than 15 cm.

The fluvisols are found along the arroyos; they show well-developed bedding, with normal gradation and variable amounts of organic matter. Their thickness is unknown since they are filling the valleys. The change in their texture and composition allows us to define the subclass.

The xerosols are dominant in the valleys. They have variable amounts of organic matter. A whitish layer at the top is characteristic of this soil, and it is usually due to the carbonate or sulfate accumulation.

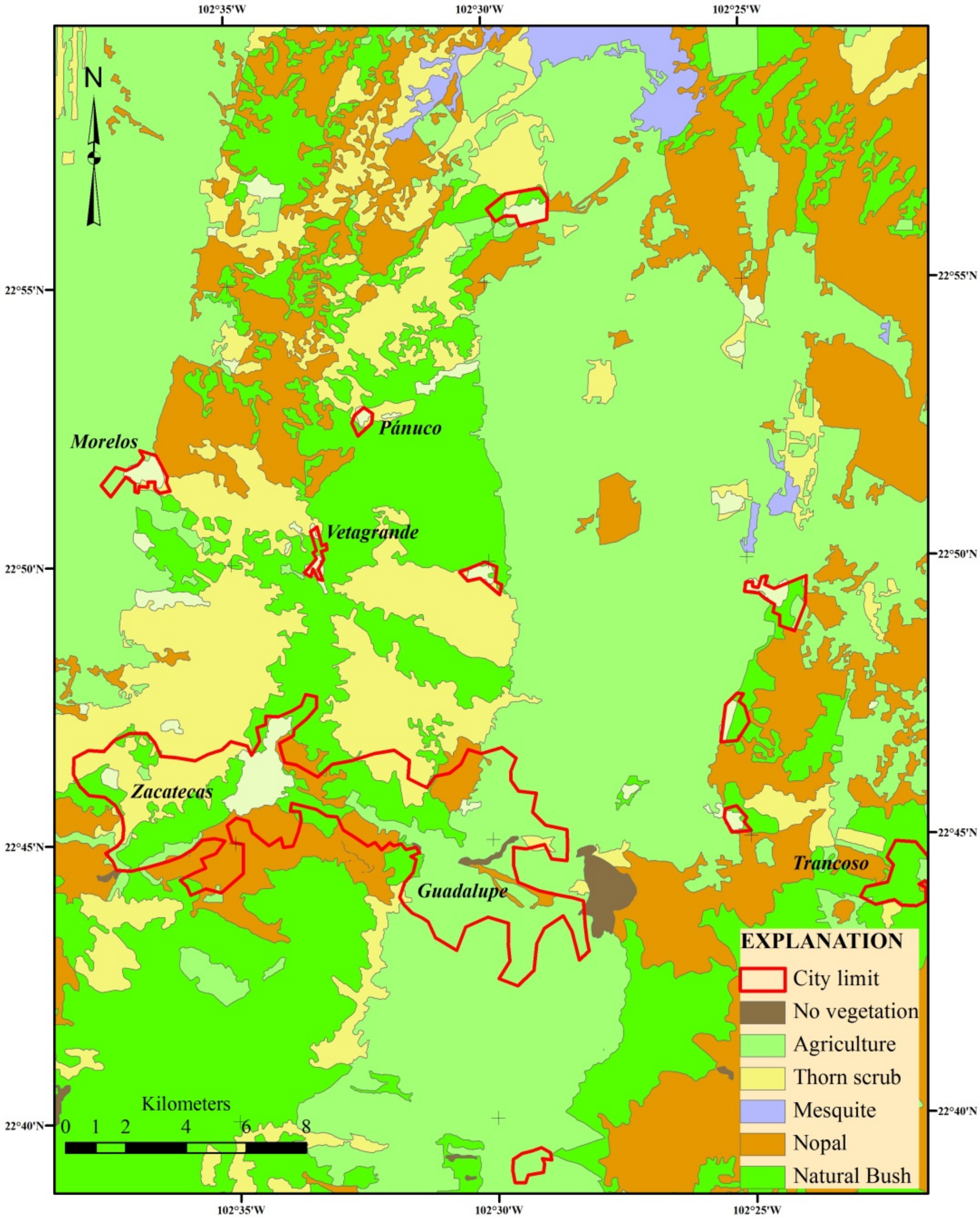


**Figure 6.** Vegetation of the study area, modified from [18-19]. The city limit corresponds to 2010. The names in bold, italics are the municipalities. The places with no vegetation are artificial dams. The original data are from the decade of 1970 [18-19].

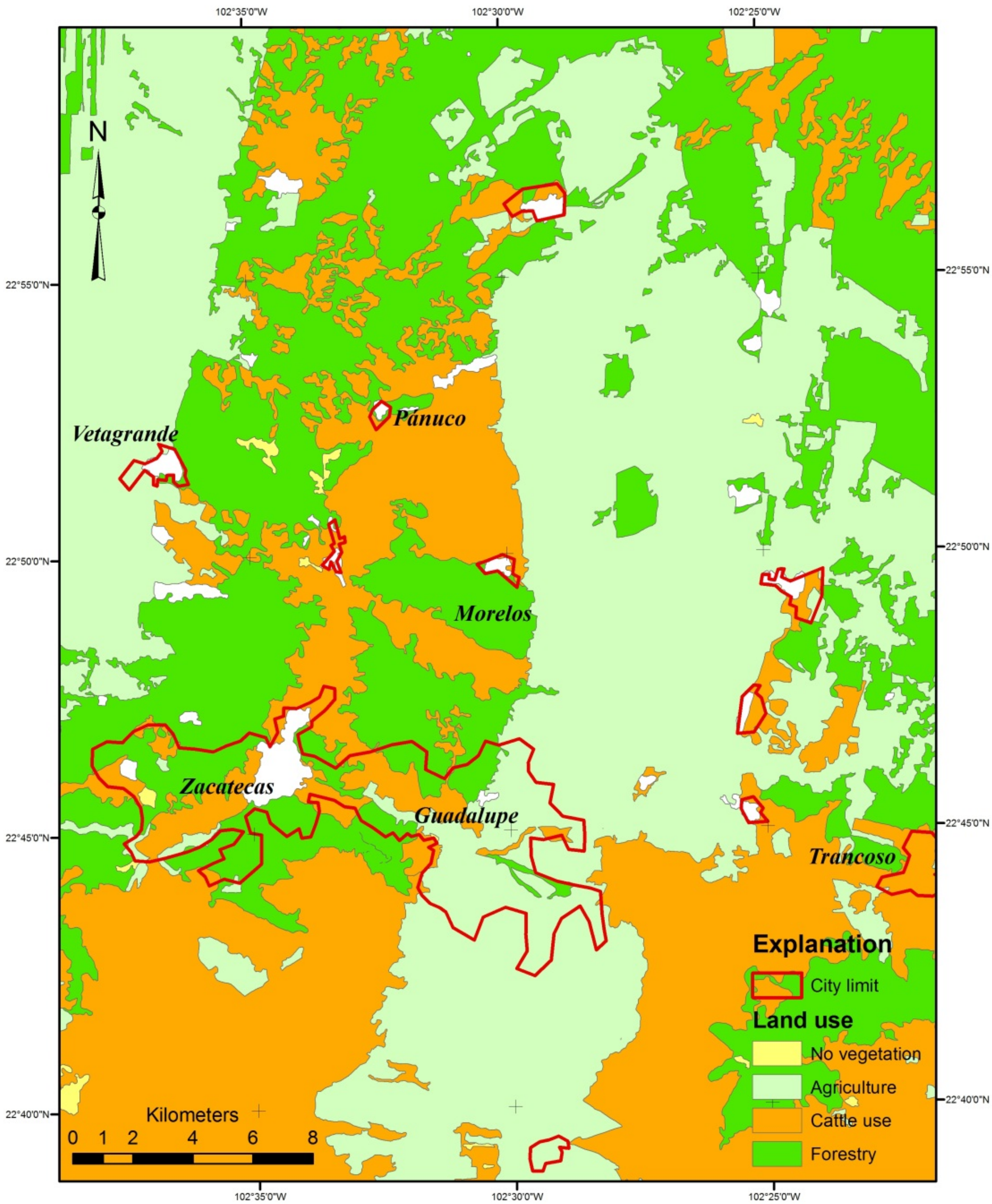


**Figure 7.** Land use proposed to the study area from [18-19]. The city limit is from 2010. The names in bold-italics are the municipalities. The places with no vegetation are the city limits in 1971. The original land use data are from the decade of 1970 [18-19].

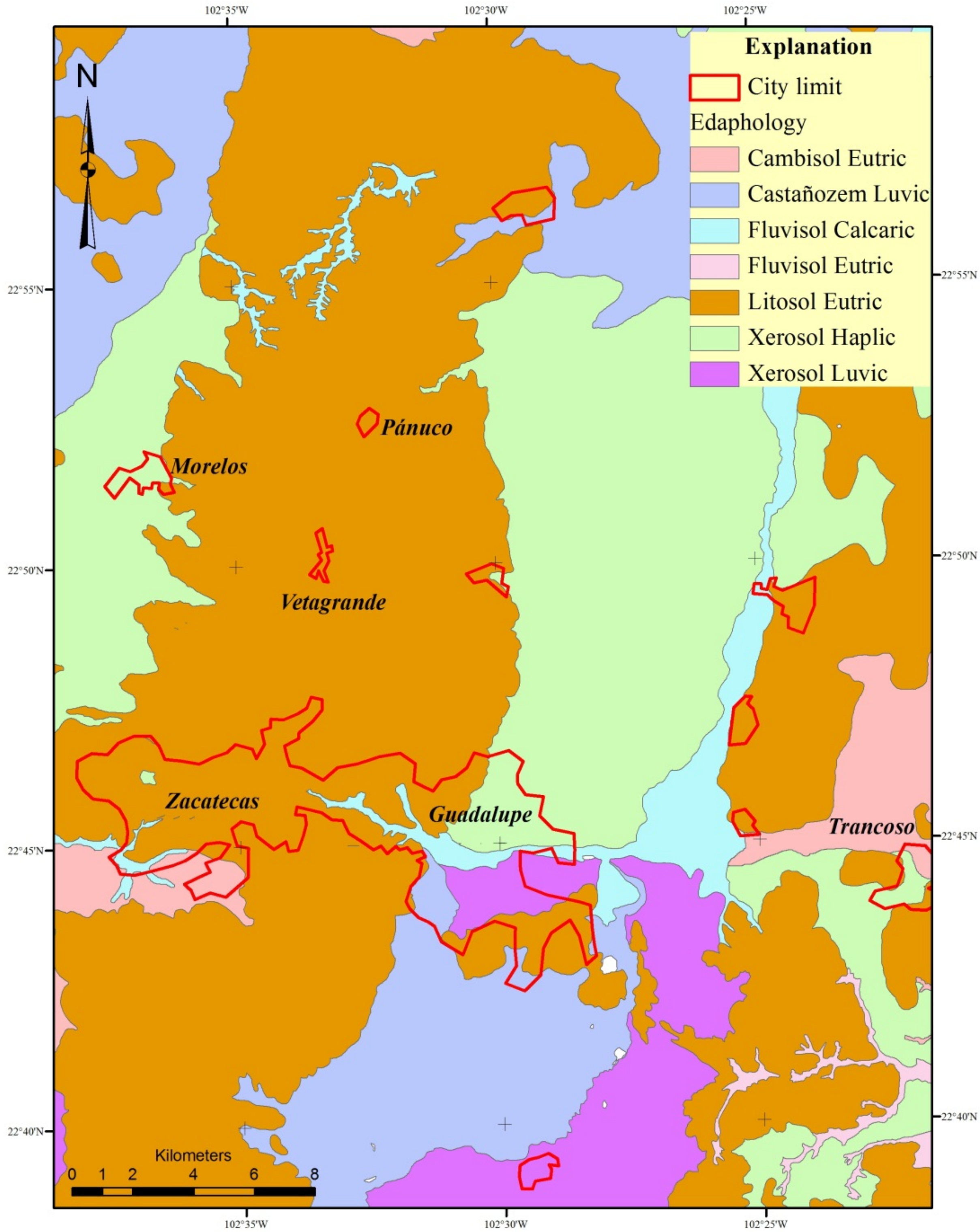


**Figure 8.** A simplified edaphologic map of the study area. Modified from [21-22].

## 2. Methodology

This chapter describes the elements used in the geologic and geomorphologic analysis. It starts with the field mapping of the elements where the hazards are occurring. These parameters were the basis for a geomorphologic study and finally all the information was integrated and analyzed in a GIS.

## 2.1. Field work

The risk areas are associated with slope deposits. The field work was directed to recognize the risk elements in the field and map them at scale 1:10,000. These elements are ancient landslide deposits and fallen rocks. They occur along arroyos, close to the top of the highest hills, and can be traced downslope until they reach the city limit.

The hazardous areas are not only related with the slope deposits; the erosion effects are accelerated where the landscape is modified, either by cutting through the hills or by filling in the arroyos. Along the arroyos are the fluvial terraces and at the edge of the Sierra de Zacatecas, the alluvial fans. In the study area all unconsolidated or moderately consolidated materials tend to be removed if their original conditions are changed.

The stratigraphic sequence and faults are mainly taken from [3, 13]. The rock falls are related with faults, steep slopes (> 20°) and rain. The rocks usually move less than 15 meters away from the source because the steep slopes are normally less than 10 m high.

In places where the cities are expected to grow, the landscape modification starts with vegetation removal, then the surface flattening, and eventually the construction phase. The cartography of the elements mentioned in this subchapter, unless when the landscape was modified artificially, where digitalized and managed in ArcGIS v. 9.3.1.

## 2.2. Geomorphologic analysis

The geomorphologic analysis was made according to the procedure described by [23]. The method uses a topographic chart scale 1:50,000 which is divided into squares; for this study the length side of each square was 1 km. In each square, four parameters were measured: 1) the dissection density (DD) that is defined as the total length of arroyos per square kilometer; 2) the general dissection density (GDD) which is the sum of the lengths of all the topographic curves per square kilometer; 3) the maximum dissection depth (MDD) which is the elevation difference measured from a creek perpendicular to the nearest highest point; and 4) the relief energy (RE) that is the difference between the highest and the lowest point in each square.

The measured parameters in each square were stored in a database in ArcGIS software. Each value is considered to be in the center of the square [23]. For each parameter, a Kriging interpolation procedure was used to define a raster image showing the spatial distribution of the variable. Since each parameter is in GIS Image format, the values can be managed for classification.

Based on field mapping, the slope deposits originated where DD> 10 km/km$^2$, GDD> 25 km/km$^2$, MDD>130 m and RE > 160. The areas defined this way were called "high erosion zones". The function used is a mathematical logical union of variables. If the variables change from 8.5 to 10 $km/km^2$, 20 to 25 $km/km^2$, 100 to 130 m and 130 to 160, respectively; they belong with the main body of the slope deposit, so they are "medium erosion zones". Whereas values ranging from 7 to 8.5 $km/km^2$, 15 to 20 $km/km^2$, 70 to 100 m, and 100 to 130, respectively, are located at the tip of the slope deposit and they are called "low erosion zones". Lower values are considered as "very low erosion zones".

The erosion areas defined this way do not take the slope into account. Therefore, due to the interpolation method used, "high erosion zones" can be located in a flat area, as well as an area with slope.

## 2.3. GIS analysis

The digital slope model (DSM) was obtained from the digital terrain model. The slopes were divided, according with field observations, in: 1) 0° to 5° semi-plain, 2) 5.01° to 10° gentle slope, 3) 10.01° to 20° hillside, 4) 20.01° to 30° ramps, and 5) >30.01° scarp or cliff. Since the DSM and the geomorphologic data are in the same coordinates system (NAD27; UTM-13N) the maps can overlay for spatial analysis. We used an intersection function of the selected DSM data with the geomorphologic analysis. This way, the DSM has redefined the hazardous areas by combining the slope ranges with the erosion zones. The intense erosion zones are located only in the scarps; while the medium erosion zones occur in the ramps and scarps. The low erosion zones are located in hillsides and ramps.

Once a result was obtained from the combination mentioned in the above paragraph, the next step was to combine the edaphology and land use information. All these areas are in the same kind of soil: Lithosol Eutric. This soil is less than 15 cm thick, rich in gravel and sand with variable amounts of organic matter. The vegetal coverage consists of bushes, nopals and grazing vegetation. When using the edaphology and land use data, the obtained results did not modify the previous outcome.

The analysis for rock falling was making a buffer of 15 meters length of the "Geology map". The structures were the result of the combination of the buffer on the fault and the slope range and direction.

All the information layers were spatially analyzed in ArcGis software, Ver. 9.3.1, and the results were verified in the field. For proof, we selected places where there were two or more erosion zones. Thus, the changes by erosion promoted by the lithology, sedimentary deposits, geologic structures, vegetation, or soil types could be observed.

# 3. Results

In this chapter all the mapping and digital analysis is integrated to get the definition of erosion zones and their relationship with hazardous zones. The obtained results were checked in the field to verify that our model is a reliable tool for urban development planning.

The basis for the analysis was the Digital Slope Model (DSM) (**Figure 9**). The cell size used was 20 m since, after testing larger and smaller sizes, that was the best dimension that defines the landscape.

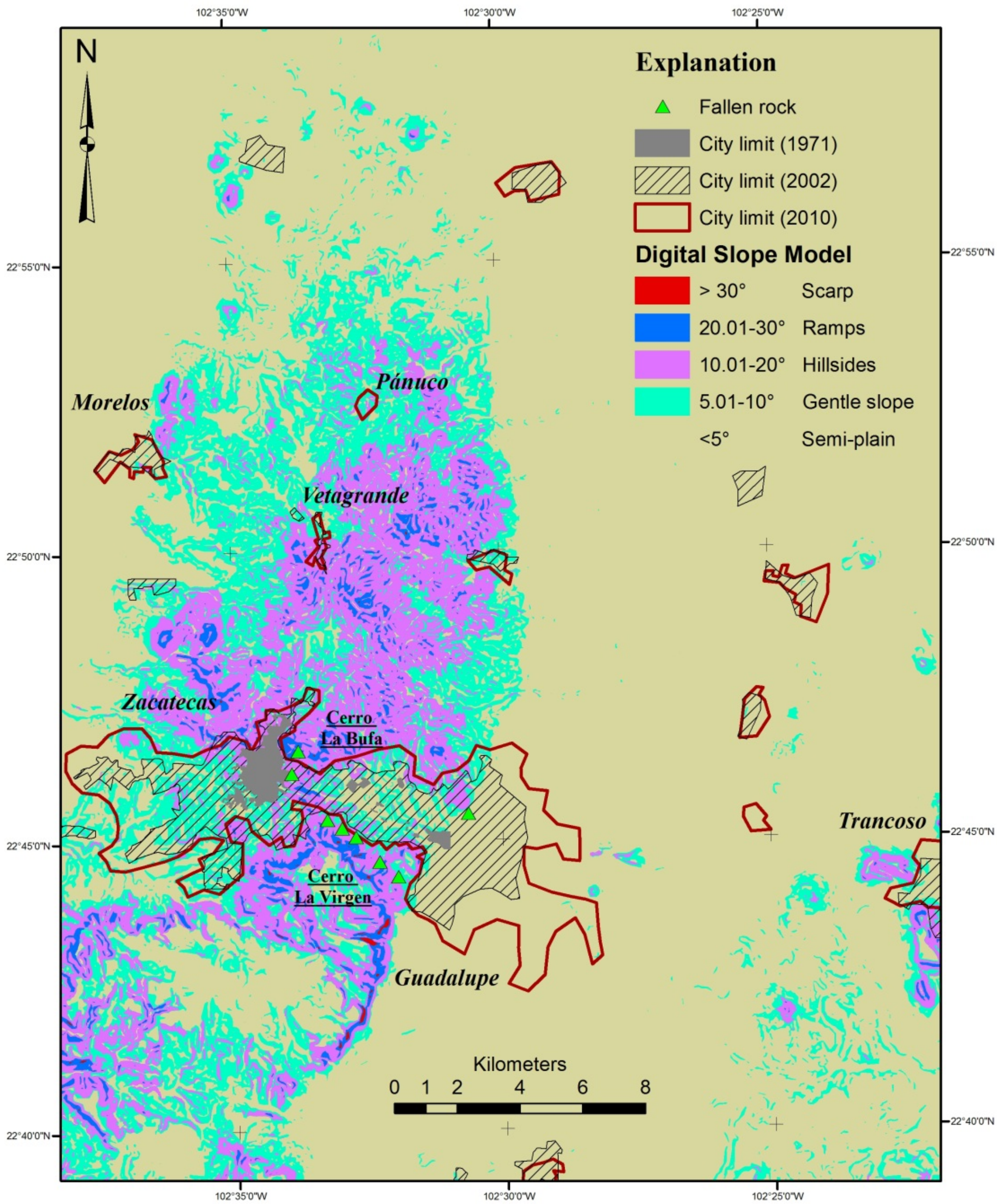


**Figure 9.** A digital slope model of the study area. The model was built using the contour lines each 10 m. The fallen rocks are those whose diameter is larger than 3.5 m. They are mostly related with ramps and scarps on Cerro La Virgen and Cerro La Bufa.

The **Figure 9** depicts the Zacatecas and Guadalupe cities growing in the gentle slope and semi-plain areas up to 2002; the use of hillsides and ramps was restricted to a few areas in Guadalupe. Due to population growth and continuous pressure on the territory, after 2002, the cities advanced toward the hillside areas. Moreover, due to the pressure on the territory, the arroyos became urbanized. The modification of the original conditions of the territory on hillsides and ramps favors the erosion on unconsolidated to moderately consolidated materials, both natural and artificial.

After 2002 the city grew in the direction of higher slopes, thus, aiding the territory to be affected by erosion. Furthermore, the city limit now is closer to scarps or cliffs where the fallen rocks become a common feature. The **Figure 9** shows the location of rocks whose diameter is over 3.5 m; however, the common ones are those of ~ 1 m that can be found upslope.

### 3.1. Geologic analysis

Rock falling is a common phenomenon in the study area. It is related with rock type and its fabric. Those rocks that are massive and deformed, if cut by faults, are most likely to be suitable for the development of this process. Additionally, the slope plays an important role in the location of hazardous areas associated with rock falling.

The analysis was made according to the observations made in modern and ancient fall rock. At present time the fallen rocks (~ 50 cm in diameter or less) observed are less than 15 m away from the fault, if there are scarps and ramps. If there is a combination of flowing water after rain with the slope, the displacement could be as far as ~ 100 m away from the source. Whereas the largest distances seen are ~ 1,000 m away from the faults (**Figure 10**).

The spatial analysis was made considering the following parameters:

1. The location of the mapped faults.
2. The lithologic units whose fabric is massive or deformed; they are: Zacatecas Formation, Deformed andesite and Undifferentiated tuff.
3. The slopes: scarp, ramp and hillslope.
4. The travel distance recorded by the fallen rocks.

The analysis is based on the location of the faults and making buffers at 15 and 100 m. The areas defined by the buffers, if they intersect ramps and scarps, are classified as hazardous zones. Due to the steep slopes no rock type was included.

The historical record indicates that a rock can travel as far as 1,000 m. For the faults mapped, this distance is in the hillslope area. During analysis, the first step was to define the buffers at 1,000 m. The next step was to perform a logical operation. If the buffer intersects a hillslope, and the lithology is considered, then the intersection identifies the area which has the possibility to have fallen rock. In **Figure 10** the areas for each distance are irregular polygons with voids inside of them. The voids are areas where the above mentioned conditions are not satisfied.

The results shown in **Figure 10** indicate the areas susceptible to have, or have the potential to be affected by fallen rocks. The field verification of these results indicates that our model defines vulnerable areas for rock falls. However, the results do not indicate the recurrence time or periodicity of the phenomena, It is merely starting where it could happen.

The hazardous areas are mostly located outside of the city limits. Additionally, **Figure 10** can be used for planning urban growth and, if necessary, make the proper preventative arrangements to avoid possible damages to the population and/or infrastructure prior to the landscape modification.

### 3.2. Geomorphologic analysis

In the Zacatecas and Guadalupe area the geomorphic agents, in relevance order, are: rainwater, gravity, wind and ice[3]. Since water is the main geomorphic agent, considering the semiarid climatic conditions, the effects of the erosion are most evident during the rainy season in the summer. In the winter, the wind and ice can increase their erosive effects in the loose materials.

**Figure 11** shows the distribution of each geomorphologic parameters. It can be noticed that during the last 40 years the cities grew on medium to low erosion zones. However, this tendency has recently changed. Nowadays, the growth is close to the limits of Sierra de Zacatecas, getting closer to the “high erosion zones”. The Dissection Density is the only parameter that barely has “High erosion” values. This is because the slope deposits start where the creeks do too; so the length of the "high erosion" is short.

The geomorphologic parameters are joined using a logical expression: If two or more “high erosion” areas intersect and the slopes and ramps are scarp, then they define an “Intense erosion zone” (**Figure 12**). The “Medium erosion zones” are defined if two or more “medium erosion” intersects with hillslope. The “Low erosion” areas are defined if two or more “low erosion” parameters intersect the gentle slope and semi-plain.

The erosion zones are defined on the basis of geomorphologic analysis and the DSM (**Figure 12**). The effects on the different lithological units, as well as the land coverage, soil type, and sedimentary deposits are verified in the field. If the natural vegetation and soil are preserved, the erosion processes do not play an important role independently of where they are located. If this is case, the surface creeping is the only geomorphic process. The vegetation and soil removal, along with the modification of arroyos and basin modifications and/or filling with unconsolidated materials, are the starting point for the erosion processes that affects the landscape.

When the original conditions are changed, the zonation that is defined here then applies. The effects are in the unconsolidated to moderately consolidated materials. There is a slow, but continuous, removal of sediments; mainly sand. The erosion occurs mainly during the rainy season in the summer. However, due to the low precipitation (~ 500 mm/yr) the monthly amount of rain could be so low that its effect as erosive agent could be minor. During the rainy season, the clay content in the sediments promotes the hydration and dehydration that, together with scarps and ramps, favors the formation of gullies.

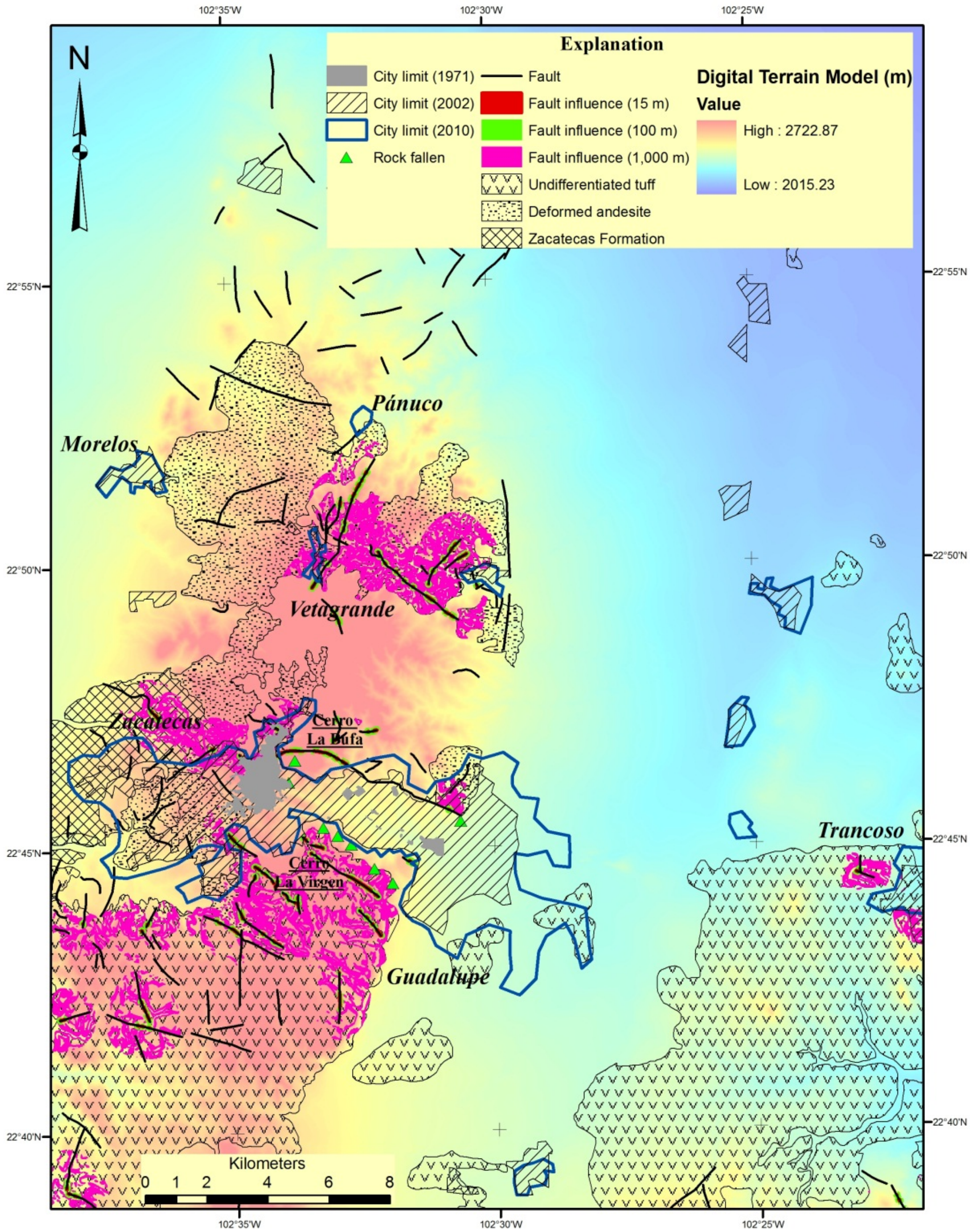


**Figure 10.** A digital terrain model showing the hazards associated with rock falling in scarps and ramps (red), hillslope close to the faults (green) and hillslope away from faults (magenta). It can be noticed that there are some faults not associated with erosion areas. This is because they are in gentle slopes or semi-plain areas.

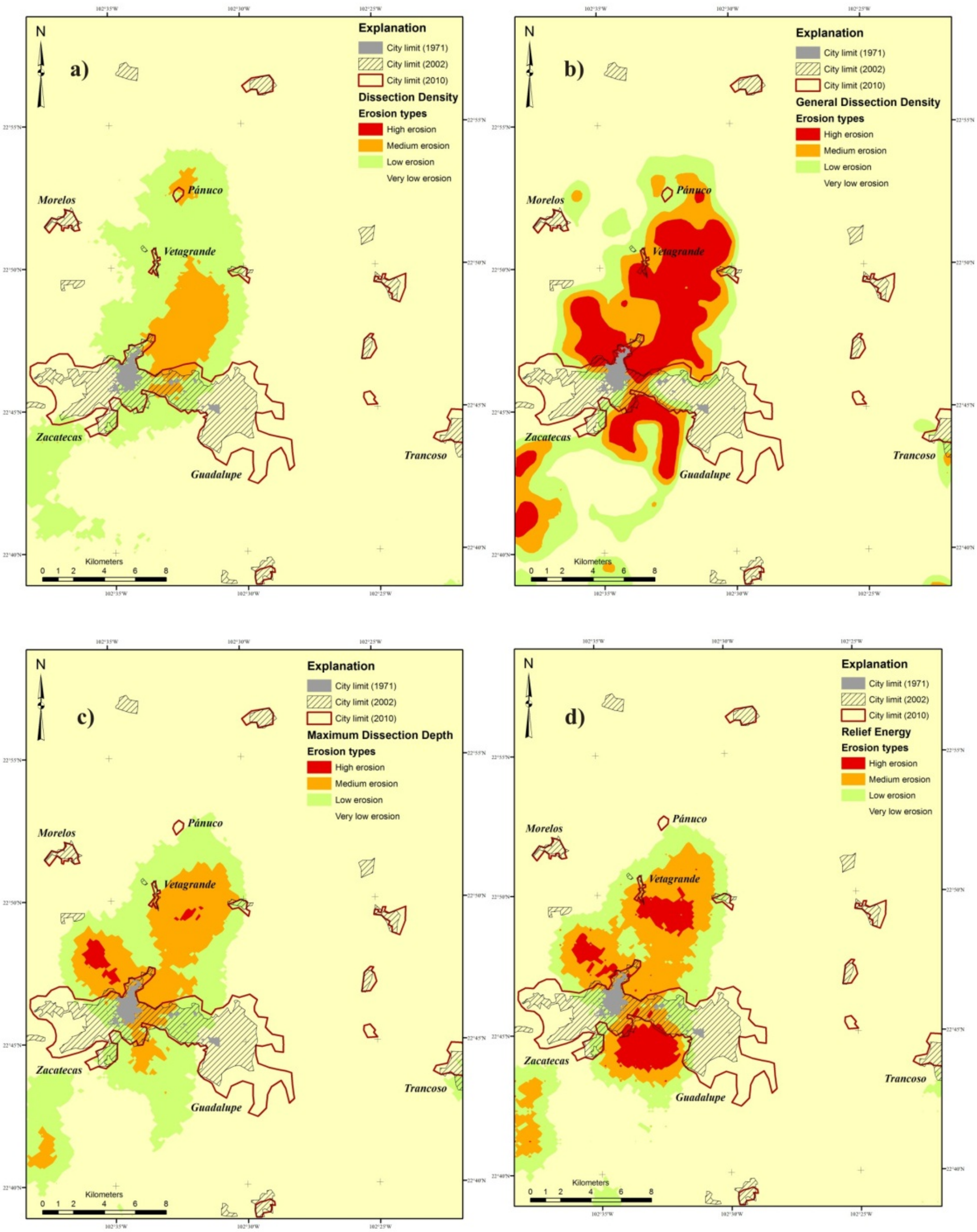


**Figure 11.** Maps showing the distribution of the geomorphologic parameters: a) Dissection density, b) General Dissection Density; c) Maximum Dissection Depth; d) Relief Energy. The erosion type values were defined according to section 2.2. Up to now, the city has grown in moderate to low erosion zones, although the "High erosion zone" is getting closer.

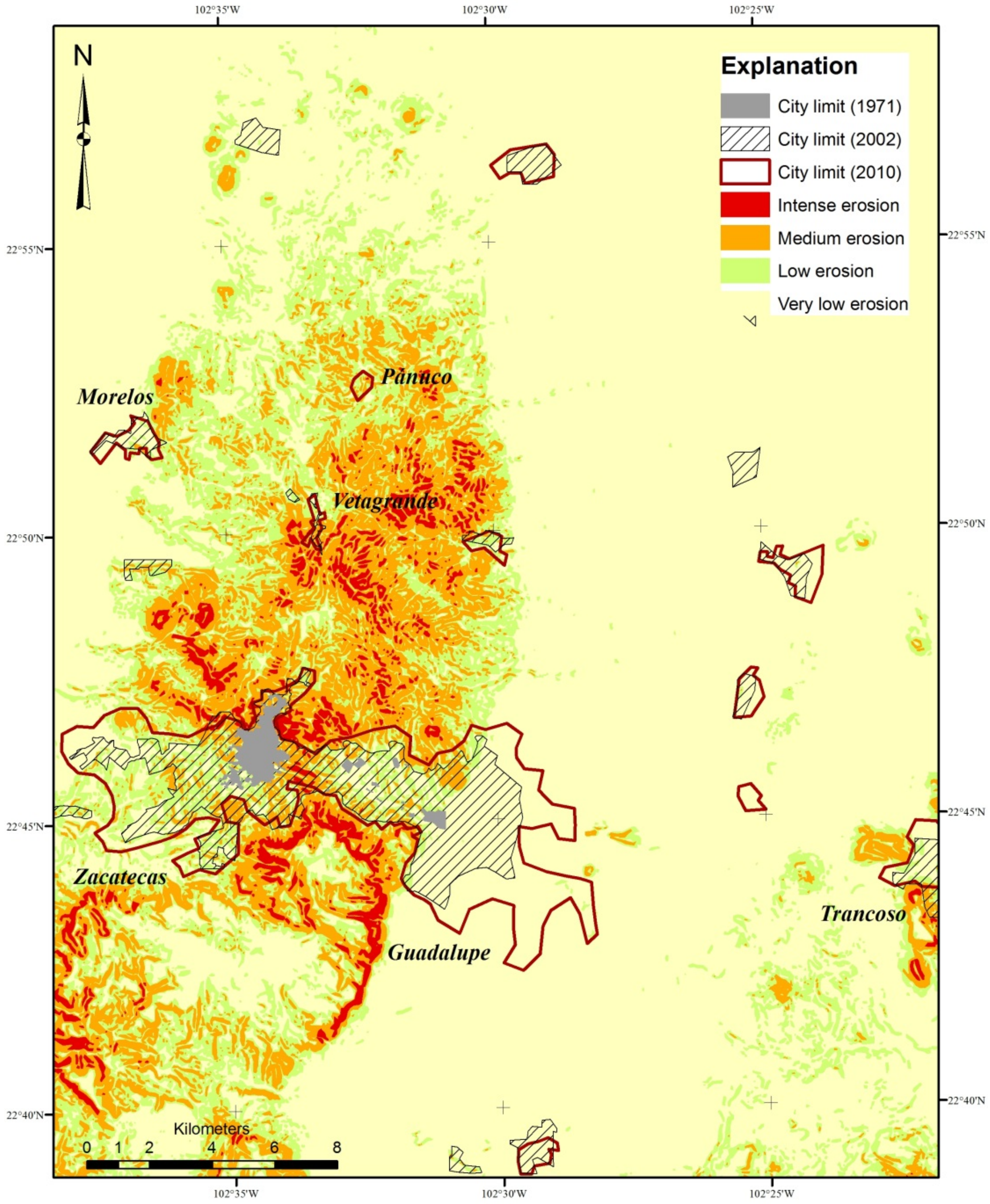


**Figure 12.** Erosion zones defined for the Zacatecas and Guadalupe quadrangles based on the geomorphologic and the digital slope model analyses. The "Intense erosion" areas indicate that if the natural conditions are changed, either by removing or adding new materials, they can be easily eroded according to the rain intensity. In the "Medium erosion" zones occurs the same event as in the previous one, but in a slower way. The "Low erosion" zones are located in the semi plain and gentle slope areas; their effects depend on the amount of running water after a rain.

The consequences of erosion in the rocks from the Mesozoic sequence and the Tertiary Volcanic rocks (both lithologic units well consolidated) are related with the faulting and fracturing patterns associated with scarps and ramps in intense and medium erosion zones. In the low erosion zones the effects are negligible. Most of the Zacatecas and Guadalupe cities are built on the Zacatecas Conglomerate whose facies composition and structure define differential erosion zones. Clearly, the sand and clay-rich facies can be more easily affected by the erosion processes than those well consolidated. The differential erosion removes the sandy rich strata, leaving unstable the conglomeratic ones or large rock fragments. With time, the unbalanced materials fall down.

The results shown in **Figure 12** were verified in the field and they are presented in **Figure 13**. The erosion removes unconsolidated materials if the original conditions are changed; otherwise the process is very slow. The velocity at which erosion acts depends on the zone they are in. The model here defined should be taken into account for the urban development planning. This model locates areas potentially affected by erosion if the landscape is modified.


**Figure 13.** Field verification of the proposed model for hazardous zones associated with erosion. a) Moderate erosion zone; in the filling deposit can be seen gullies formed after the rainy season; whereas the conglomerate is affected by differential erosion. b) Intense erosion zone. An excavation was made

for unknown reasons. The effects after the rainy season were that the wall and sidewalk fall. c) A Low erosion zone in a semi plain area; more than one year after the road was built, large gullies developed. d) An intense to moderate erosion zone. The undisturbed area is in the intense erosion where no visible effects are seen; while the moderate one is where the streets are traced.

## 4. Conclusions

If the landscape is not modified, the only erosion process acting is the surface creeping. This is independent of the location of the erosion zone. In the intense to medium erosion zones the mobility of loose materials is mainly achieved by rainwater when: 1) the landscape is modified, 2) the road cuts have a high angle or high angle slopes, 3) in the moderately consolidated facies of the Zacatecas Conglomerate, and 4) in the sedimentary deposits. The vegetation, land use and edaphology seem not to have any significant outcome in the definition of the erosion zones.

In the well consolidated rocks, the effects of the high erosion zones are associated with faults and fractures. In the historical record, rocks of less than 1 m in diameter can travel as far as 1 km away from the source rock in scarps to hillslopes. The model here presented detect the areas with strong possibilities of having fall rocks fallen.

The low erosion areas only have an effect in loose materials; while in the very low erosion zones the effects are along the arroyos.

## 5. Further research

After this study several questions were answered, but new ones arise for further research such as:

1. Until now no geophysics method has been used to define the extent and depth of the slope deposits, fluvial terraces, alluvial fans and artificially filled places. A method that could be used is surface waves, in this way the elastic parameters of the unconsolidated sediments could be obtained and may be used in construction regulations. The surface waves could also be used to locate buried slope deposits.
2. The slope deposits are of unknown age; they could be dated by looking for fossils, using U-Th-He, cosmogenic isotopes and/or paleomagnetism. The knowledge of their age and recurrence could be useful in defining the hazards´ recurrence.
3. The geomorphologic parameters used allowed us to define the erosion zones if the topography is abrupt; however they are not designed to evaluate the almost flat surfaces of the valleys. A further work is to look for the parameters that could be used to evaluate erosion in the valleys.
4. In the places damaged by the erosion processes, it is necessary to develop a mitigation plan. This should be made by an interdisciplinary professional team.
5. It is necessary to define the unconsolidated material loss; either from soil, fillings, sedimentary deposits or unconsolidated materials. In this way it could be possible to

make a precise evaluation of the sediment removal and the location of the more likely places where it will occur.

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