Chapter 4

Methodology of Sustainable Environmental Planning in Rural Areas (SEPRA)

4. Model of spatial analysis for the Sustainable Environmental Planning in Rural Areas (SEPRA)

The conceptual and technical approach of the spatial analysis model for the Sustainable Environmental Planning of Rural Areas (SEPRA) was already presented in Chapter 2. In the following the model of spatial analysis is formulated. The general fundaments, the technical structure of the proposed model, and the required input data are introduced. The model can be defined as a technical tool addressed to support the decision-making process related to the environmental planning and the sustainable development of rural areas.

4.1 Conceptual framework

The principal theoretical fundament of this method can be described as an integral and holistic conception of the environment in which the landscape is considered as the final product of a series of interacting factors, including climate, relief, water, soil, natural flora and fauna, and human actions. The result of these spatial and temporal interactions is a specific spatial layout of environment ecosystems in aesthetic and functional terms, which characterizes each territory (Sayadi et al., 2009; Renschler et al., 2007). Moreover, it is accepted that the complex and dynamic interactions between physical, biotic and socioeconomic environmental components result in given conditions of stability or instability whose analysis allow the land-use possibilities or restrictions to be identified. Indeed, today’s environmental managers, planners, and decision-makers are expected to examine environmental and economic problems in a larger geographic context to: 1) to understand the scales at which specific management actions are needed, 2) to conceptualize environmental management and planning strategies, 3) to formulate sets of alternatives to reduce environmental and economic vulnerability, as well as the uncertainty in their evaluation analyses, and 4) to prioritize, conserve, or restore valued natural resources, especially those which provide important ecological goods and services (Kepner et al., 2000). This requires a holistic and interdisciplinary approach (Simpson et al. 2001; Thoms and Parsons, 2002 cited in Vanacker and Govers, 2007; Sayadi et al., 2009).

The conceptual model developed in this study (Figure 4.1) is based on the formulation of the associations among the environmental features as a result of an inductive strategy of observation and environmental assessment (Böhn and Schütt, 2002). In this model some important interrelations between several *factors* and environmental *processes* are identified. The *factors* are those environmental components whose conditions can be characterized as permanent or quasi-permanent. This is the case, for example, of geological faults or landforms. The *processes* are those environmental features characterized by a changing temporal behaviour. Although most of these changes can be identified within given and known thresholds, their foresight is frequently affected by an important grade of uncertainty (Burton, 2001). Therefore, it is always a challenge for the environmental sciences and normally one of the keys of success of the environmental planning is to reduce this uncertainty and obtain a better predictability of environmental behaviour (U.S. Climate Change Science Program, 2003). In this sense rainfall, earthquakes and land use may be mentioned.

In the relations among environmental features it is also important to identify triggers and damages. Triggers refer to processes when actions on factors activate changes to the environmental system. Damages are the resulting processes characterized by negative effects for the stability of the environmental system.

In the conceptual framework it is considered that earthquakes, rainfall and land use are important triggers whose conditions and behaviour influence the dynamics of the environmental processes. Earthquakes, for example, according to their intensities, can generate mass movements as a consequence of given conditions of the lithology, slope, soil, vegetation cover or land uses. Likewise, rainfall according to given circumstances of relief, soil, vegetal cover or land uses, can greatly affect environmental stability (Nadim and Lacasse, 2004).

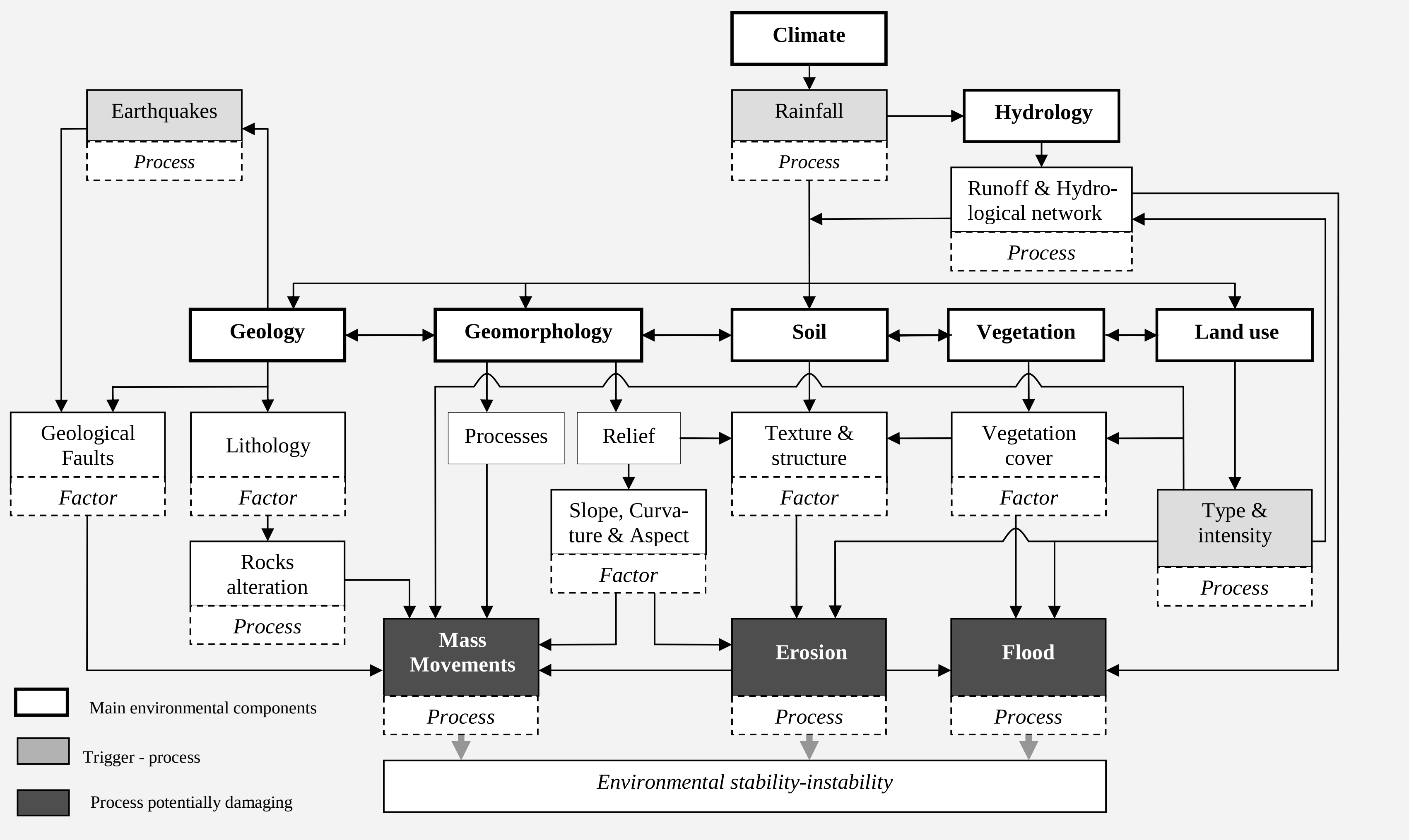


Figure 4.1: Conceptual framework of the interactions between environmental factors and environmental processes.

The land use, as one of the most important variables for human impacts, is above an important trigger of environmental processes and damages. Depending on its type and intensity, land use significantly affects the environmental conditions, causing transformations and environmental impacts.

4.2 Technical structure of the Spatial Analysis Model (SEPRA)

A general overview of the methodology with the considered environmental features and the needed steps is presented in the flowchart in Figure 4.2. For the selection of the environmental features to be considered in the proposed spatial analysis, the following have been considered:

1. The selected environmental features contribute significantly to configure the environmental conditions of rural areas.
2. The primary or secondary information of the selected environmental features is normally recorded and provided by public or academic institutions of the region where the study areas are located. Also, some of this information can be obtained from databases freely available on the internet. It makes the methodology highly useful and facilitates that it could be replicated in other rural areas.
3. The environmental features can be assessed by means of accessible methods and interpretations technically supported.

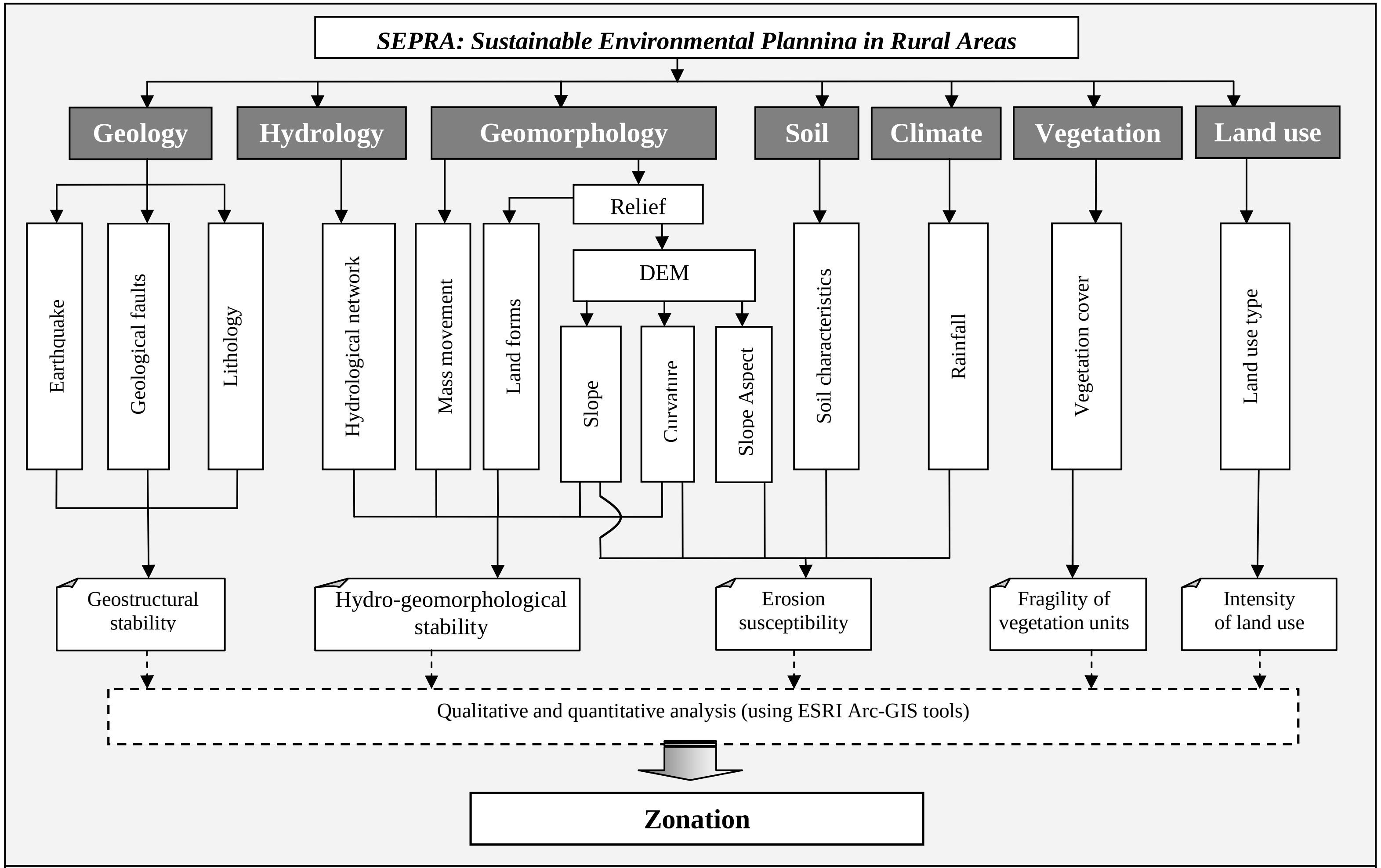


Figure 4.2: Model of spatial analysis for sustainable environmental planning in rural areas.

4.3 Input factors

4.3.1 Geology

The geological background is of fundamental importance within the environmental systems. Its special incidence is either significant for the geomorphological processes, the relief, the soils or even anthropogenic uses. The importance of geological analysis is well recognized in order to foresee risks with respect to constructions such as dams, railways, buildings, landfill or airports (Fountoulis et al., 2003; Klügel, 2008) and even for the inventory and exploitation of mineral resources. Traditionally, geology constitutes a standard component in environmental assessment methods. Thus geological maps give information of the rock composition and rock mass strength (Carrara, 1999; Van Westen el al., 2008).

In environmental planning of rural areas the geological aspects provide information through which conditions of land stability, risks and natural hazards, and the possibilities or limitations for the land uses can be inferred. In this methodology, earthquakes, geological faults and lithology have been considered as indicators of the geological conditions of the study areas.

4.3.1.1 Earthquakes

Earthquakes are major natural processes of high destructive potential, often result in both, human and material losses (García-Rodríguez et al., 2008). The earthquakes threaten environmental stability and increase natural hazards. Due to the earthquakes, structures and properties can be severely damaged and even collapse which should be taken into consideration when designing new structures (Han and Choi, 2008) or to carrying out environmental planning processes.

As earthquakes cannot be avoided, it seems to be more important to design and apply strategies in order to mitigate their effects, rather than be able to forecast their occurrence. Thus, to prevent the hazards and consequences of the earthquakes it is a principal interest of the planners. However, zonation of most geological hazards and prediction of their risks remain as largely unsolved problem (Carrara et al., 1999).

One of the most important aspects of earthquakes is their high potential to generate mass movements. Bommer and Rodríguez (2002) emphasize that the destructive impacts of earthquakes in many parts of the world is greatly increased by the occurrence of landslides during or after the shaking. The same authors state that after the direct effect of structural damages, landslides are the most important consequence of earthquakes. As well as causing disruption of the communication infrastructure, earthquake-induced landslides can contribute significantly to the death toll.

The required information of the earthquakes is normally provided by earthquake catalogs recorded by public or academic institutions and is frequently available on the internet. In Venezuela some research institutes offer complete and useful information about seismic activity, among these are: Laboratorio de Geofísica - Universidad de Los Andes, Mérida, Venezuela (http://lgula.ciens. ula.ve/), Fundación Venezolana de Investigaciones Sismológicas (http://www.funvisis.org.ve/) and Centro Regional de Sismología para América del Sur (http://www.ceresis.org). Figure 4.3 presents an overview of the main geological fault systems and the network seismic stations located in the Venezuela west.

It can be emphasized that the study areas are located along the most important and active geological faults of western Venezuela; therefore, the areas are characterized by high seismic activity.

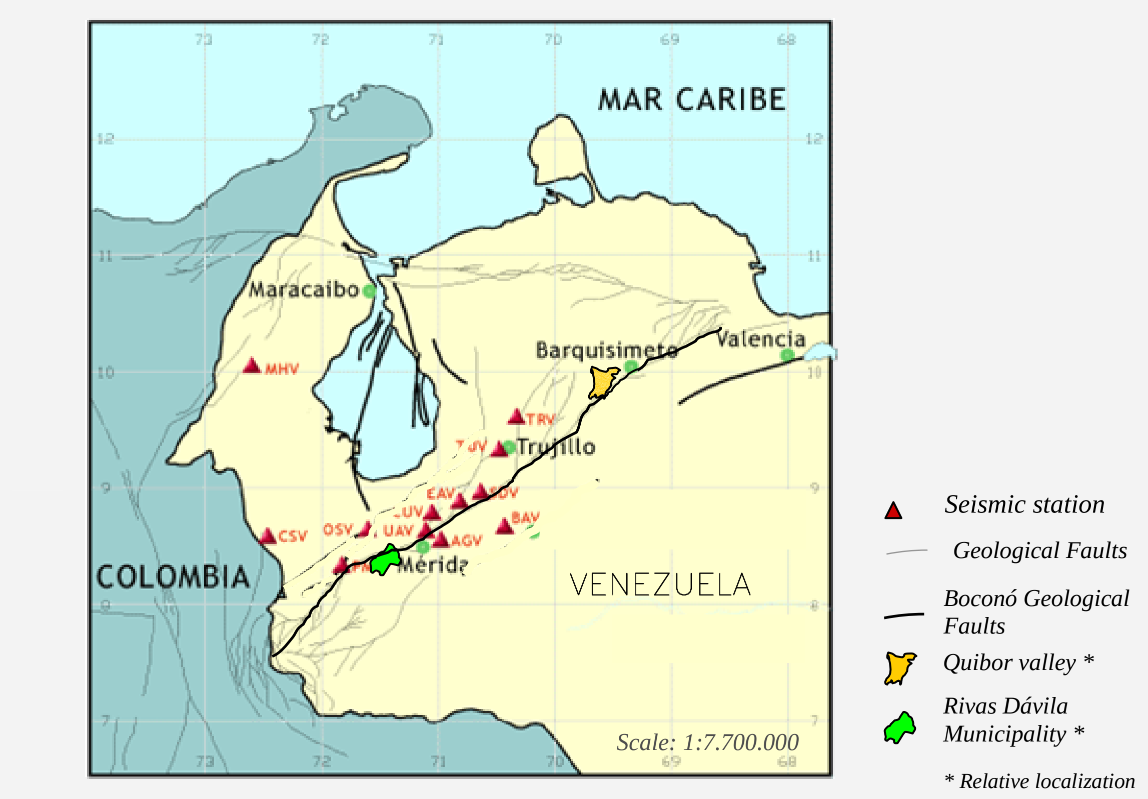


Figure 4.3: Seismic network and main fault systems of the Venezuelan west.

Source: Modified after ULA (2008).

4.3.1.2 Geological Faults

In the evaluation of the exposure to earthquakes of an area, it is fundamental to consider the presence or absence of geological faults. It is widely admitted that, apart from volcanic zones, the occurrence of earthquakes has higher probabilities in areas with geological faults, just where the resulting energy of the geological plates compressions is liberate (Schubert, 1982; Wang, 1997; Gisler et al., 2004; García-Mayordomo, 2007).

Geological faults can be seen as important indicators of the stability grade of a given area because of their direct effect on rock fracturing and landslides. Thus, geological fault information is used frequently in landslide hazard assessments (Abdallah et al., 2005; Van Westen et al., 2008) as well as it being a highly useful variable in the design, construction and performance of a wide variety of engineering projects (Bonilla, 1988). Additionally, Goethals et al., (2009) suggests that tectonic activity enhances erosion when it is associated with the production of relief and steepening of hillslopes.

Moreover, the instability of areas with active geological faults is not only a product of very intense earthquakes, but is also caused by the permanent and, sometimes, imperceptible telluric movements. Thus, it is quite obvious that the disturbance effect of the faults on the terrain instability is highly important, for example, as a trigger of landslides (Gokceoglu et al., 2007).

In order to analyze the threatened area by geological faults the following steps are considered: 1) to identify the location of fault lines, 2) to establish risk zones according to a given distance, e.g. 500 m, and 3) to create buffer zones around them. The obtained area should be considered as more susceptible and affected by the seismic activity. By means of several GIS tools these buffer zones can be defined. With respect to this, Van Westen et al. (2008) state that the use of wide buffer zones around faults is especially useful in cases of active faults. In other cases the designation of a narrower buffer zone may be more adequate. It is expected that in those buffer zones the rocks are more fractured as a consequence of the seismicity.

For this analysis the tool *buffer (analysis)* provided by ESRI ArcGis is used. This tool creates a buffer polygon to a specified distance around an input feature which, in this case, is the fault line. The recommended distance around the faults was 500 m on both sides. In regards to this, Gokceoglu et al. (2007) observed a systematic decreasing of terrain instability and exposure to landslides depending on the distance, identifying at the same time a highest instability in the zone of 0-500 m zone around the geological faults.

4.3.1.3 Lithology

The lithological instability can be defined as the natural tendency of the bedrock to present conditions of fracturing, weathering or collapse. This instability depends on intrinsic conditions such as type of rock, strength or hardness, as well as extrinsic factors such as climate or slope inclination. Thus, the bedrock characteristics and their stability conditions have an important function in the configuration of environmental stability.

It is recognized that the lithological characteristics such as rock strength or hardness have significant influences on the weathering of the rock and consequently in the occurrence of mass movements, erosion or even affect the development of engineering projects (Vargas, 1999; Kojima and Obayashi, 2006; Fourniadis et al., 2007; Shalabi et al., 2007).

Moreover, the degree of rock sensitivity to moisture content determines the possibilities of fracturing, collapse or structural disintegration of the rocks. Studies have shown that increases in moisture content have a conspicuous effect on both $^{\text{the}}$ strength of the rocks and deformability (Hawkins and McConnell, 1992), from which highly the stability of the mass rocks in the slopes depends greatly (Read, 2008).

For large areas in Venezuela, an overview of the lithological characteristics can be obtained from geological maps and stratigraphic lexicon elaborated by official institutions like the Ministry of Energy and Petroleum or the national petroleum company PDVSA. This information, as well as the research works carried out by Dugarte (2002), SHYQ (2004) and CIDIAT (2004), provided the basic information utilized in this study to identify the geological characteristics of the two study areas.

4.3.2 Geomorphology

Geomorphology plays a fundamental role in controlling many ecosystem processes, and in turn, ecosystems can have a profound influence on many geomorphic forms and processes (Reschler et al., 2007). Therefore, to recognize and to analyze the geomorphologic characteristics of a region is fundamental to be able to understand and explain the processes that govern the environmental stability. Subsequently, it will be possible to prevent or mitigate their frequent impacts on man-made structures (Arnaud-Fassetta et al., 2005; Wang et al., 2005).

Within the geomorphological aspects, relief and geomorphological processes have been considered in this work. Specific relief characteristics such as slope, curvature and orientation of the slopes (aspect) have been also been helpful in the analysis of the geomorphologic features.

4.3.2.1. Relief

Land surface has its principal expression through the relief. This is the vertical dimension of the terrain which defines the land form. It can be evaluated and measured by several parameters such as elevation, inclination, longitude, shape and orientation. Relief represents one of the fundamental features to be assessed in any environmental characterization because of its contribution to understanding the both ecological and socio-cultural characteristics of the landscapes, e.g., those areas with very steep slopes offer more restrictions to the anthropogenic interventions. For the spatial analysis proposed in this work land form, slope, curvature and aspect are considered.

4.3.2.1.1 Land Form

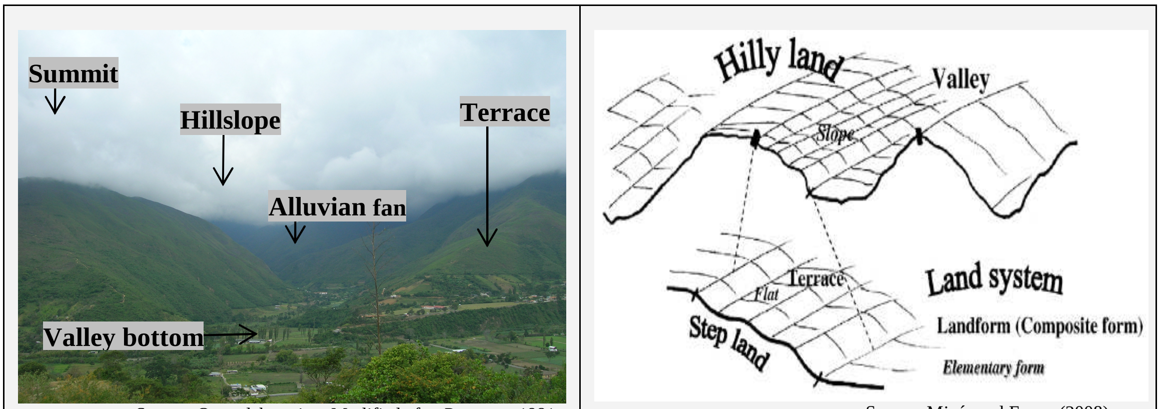
The classification and description of land form is a necessary part of the geomorphologic characterization. Identification of elementary landform units is important not only in the study of the past and present geomorphic processes but also in the study of interactions among landforms, soil, vegetation, climate and hydrological regime (Irvin et al., 2000; Blaschke and Strobl, 2003 cited in Minár and Evans, 2008). By means of land forms, several landscape types, which provide a satisfactory knowledge of environmental structures and processes, can be defined (Culling, 1988).

In the definitions of the land forms, the following features will be considered: 1) the terrain position in the watershed, 2) the shape of the relief, 3) the age and kind of the Quaternary deposits, or even 4) the character of the bedrock outcrops.

Due to the fact that land forms are closely related to the landscape conditions, their description contributes with the delimitation and interpretation of the environmental characteristics of the land unities.

In order to distinguish the forms of the land surface it is necessary to consider that the different segments should be genetically and morphologically homogeneous (Minár and Evans, 2008). Irvin et al. (2008) proposed the following five segments to identify land forms: summit, shoulder, backslope, footslope and toeslope.

These spatial delimitations are usually determined by means of aerial photographs, satellite images and or field observations, based on elevation and profile curvature. In this sense the Digital Elevation Model (DEM) and its derivatives i.e. slope, aspect and curvature are widely utilized tools. Thiemann (2006) identified geomorphological units in Ethiopia based on the characteristics of relief morphometry and climatic conditions. A first land forms classification could be integrated for some of the basic altitudinal positions within a drainage basin: summits, plateaus, hillslopes and valley-bottoms (Figure 4.4).



Source: Own elaboration, Modified after Peterson, 1981

Source: Minár and Evans (2008)

Figure 4.4: Land-forms classifications.

These land-form types can also be characterized and divided into more categories, considering parameters such as slope, curvature, altitude, geomorphological processes, land use, vegetation cover or climate. With respect to this, Schütt and Thiemann (2001) recommended for a first level (major landforms): mountain, hill, plateau, basin, valley, plain and escarpment, while a second level could be integrated by: alluvial plain, peneplain, volcano, pediment, lacustrine plain and delta.

4.3.2.1.2 Slope

Slope is defined by a plane tangent to a topographic surface (Borrough, 1986 cited in Brardinoni, 2008) (Figure 4.5) and constitutes a fundamental parameter of relief measuring. Through the slope the rate of altitudinal change of the terrain is valuated with respect to a given horizontal distance. Thus it determines the inclination grade of the land surface. Consequently this helps to evaluate some other environmental characteristics such as susceptibility to erosion processes or natural limitations to anthropogenic interventions. Schütt et al. (2007) according to Wild (1995) emphasize the impact of the slope on the sensitivity of the landscape towards the erosion, which influences the splash effect of the raindrops on the one hand, and the velocity of the runoff of surface water, on the other. Therefore, it is accepted that slope gradient is a dominant property in influencing soil erosion (Li et al., 2007).

In the applied spatial analysis method, the evaluation of the slope is addressed to determinate its incidence on the stability-instability conditions of the land. This implies to accept that environmental restrictions and the natural hazards increase with the increase of the terrain inclination. However, the instability of the slopes also depends on other factors such as land cover, lithology, climate and hydrological conditions. Thus, the most common triggering mechanisms for slope instability on land, other than gravity, are climate, and especially rainfall; earthquakes and human activities (Nadim and Lacasse, 2004).

Slope may be expressed either in percentage (%) or degree. The first form measures the vertical changes gradient in relation with the horizontal plane; the second value measures the angle formed between the curve and the horizontal plane. In Table 4.1 a convenient classification of the slope for mountains regions is presented.

Table 4.1. Slope classification

Description	Percentage (%)
Level to Gently Sloping	< 3
Gently Sloping to Undulating	3 – 8
Undulating to Rolling	8 – 18
Rolling to Hilly	18 – 30
Steep Hill and Mountain	30 – 50
Very steep	> 50

Source: Modified after Vargas, 1998; Schütt and Thiemann, 2001; Schütt, 2006.

4.3.2.1.3 Curvature

Curvature concerns the gradient of change in the curve described by the land surface in terms of concavity, convexity and straightly. Its importance as parameter to describe the landforms is widely accepted (Minár and Evans, 2008). It may be differentiated between profile curvature, plan curvature and complex curvature (Schütt and Thiemann, 2001):

1. *Profile curvature* describes the flexion of a slope surface from top to bottom. Negative values indicate convex profile curvature; positive values indicate concave profile curvature, while cero indicates a straight or linear profile.
2. *Plan curvature* describes the contour parallel flexion of a slope surface. Negative values point to concave profile curvature, positive values to convex profile curvature, and zero indicates straight or linear plan curvature.
3. *Complex curvature* also describes the flexion of a slope surface from top to bottom as the contour parallel flexion; it is generated by building the difference between plan curvature and profile curvature. Negative values point to a highly concave profile curvature of the slope segment; while at the same time, plan curvature is also highly concave. Vice versa positive values point to a convex profile and plan curvature.

An overview of the most frequent behavior of profile and plan curvature is shown in Figure 4.5.

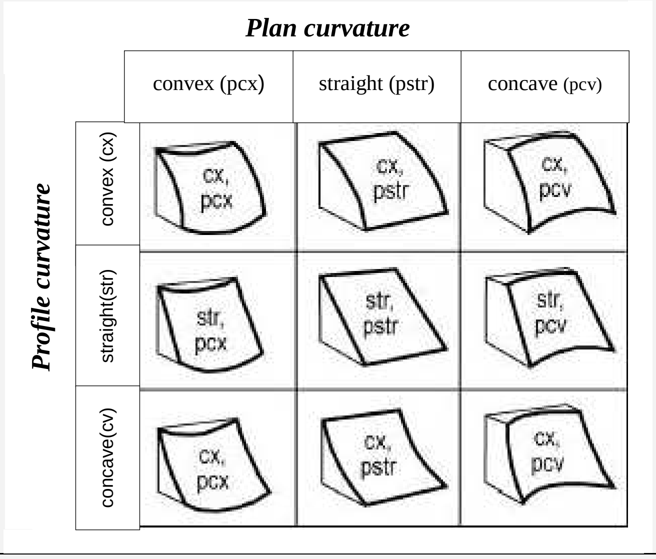
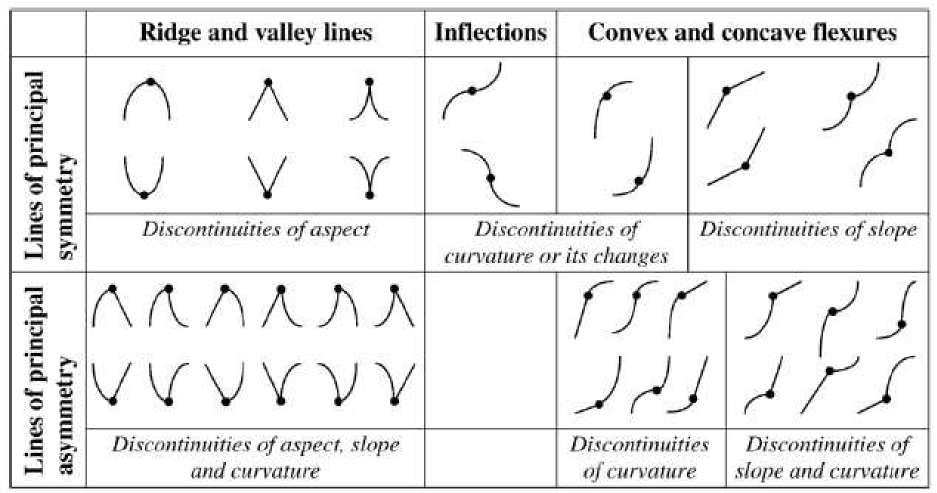


Figure 4.5: Cross slope and down-slope component.

Source: Schütt and Thiemann (2001).

Theoretically, the classic hillslope profile is a convex upper section and a concave lower section, unless the upper section of the slope is controlled by a resistant cap, in whose case the concave profile commences at the top of the slope (Loch, 2005). Most slopes, however, consist of a sequence of convex, concave, and uniform segments (Di Stefano et al., 2000) which can have a very big variety of land forms (Figure 4.6).



4.6: Profiles across types of structural lines after Lastoczkin (1987), and their interpretation as lines of discontinuity.

Source: Minár and Evans (2008)

The curvature characteristics of the slopes depend on several factors and environmental processes such as bedrock types, altitude, geomorphologic processes, climate, vegetation cover or land-use.

Regarding the established relationships between slope curvature and erosion, curvature analysis contributes significantly to explaining the environmental phenomena of stability-instability.

Di Stefano et al. (2000) state that the shape of a hillslope affects the rate of erosion at different locations along the slope, but at the same time, erosion along a slope changes the slope shape as erosion progresses. Thus, it is accepted that typically the erosion processes result in soil loss from convex segments of the hillslope and soil accumulation within a concave position (Li et al., 2007). Convex curvatures produce the highest sediment yield and, consequently, are the slope forms most affected by erosion process (Young and Mutchler, 1969; Siepel et al., 2002; Reike and Zapp, 2005). Siepel et al. (2002) concluded that concave slopes show pronounced soil loss at the top slope and deposition at the foot slope.

According to Shary et al. (2002) cited in Thiemann (2006) profile concave and plan concave relief elements are causing converting overland flow, and thus increase the energy of surface runoff. In contrast, profile convex and plan convex relief elements are diverting overland flow and here the energy of surface runoff decreases. Increasing surface runoff energy causes erosion, whereas decreasing energy leads to accumulation.

4.3.2.1.4 Slope exposition (Slope aspect)

Due to the importance of the solar radiation for the ecosystems and the environmental processes, the analysis of the slope orientation with respect to the sun's position throughout the year is widely useful in the environmental studies. In the northern latitudes the south-facing slopes may receive six times higher solar radiation than north-facing slopes. Although located only a few hundred meters apart, the microclimatic conditions on the slopes vary dramatically, affecting the biology of organisms at all levels (Auslander et al., 2003), but also other environmental features (Cano et al., 2002). In these regions one of the most important differences between north- and south-exposed slopes consists precisely in the greater vulnerability of the south-exposed slopes to erosion (Munro and Huang, 1997; Carrara and Carroll, 1979; Khasanovich and Mahmudovich, 2008). In the southern latitudes instead, the north-exposed slopes are the most likely to be affected by erosion processes (Hughes, 1972).

In tropical regions, however, the differentiated incidence of the solar radiation is actually perceptible between the east-exposed slopes and west-exposed slopes. Thus, throughout the year, morning solar rays radiate intensively on the east-exposed slopes (sunny slopes), whereas the west-exposed slopes (shady slopes) receive the solar radiation from midday, when the exposure may be reduced by cloudy conditions (Mejia and Vera, 2001; Martínez, 2008).

As a result, microclimatic differences are generated. Unless local factors dictate otherwise, a sunny slope will be frequently warmer, dryer and potentially more vulnerable to erosive processes than a sheltered shady slope. Instead, a shady slope will be potentially fresh, humid, and covered by dense vegetation. Consequently, this slope has minor vulnerability to erosive processes (Zamora, 2002; Ayala et al., 2007; Martínez, 2008). In order to evaluate the relationships between aspect and erosion vulnerability in the study areas of this work, the following empirical references are proposed (Table 4.2):

Table 4.2: Aspect classification

Aspect	Vulnerability to erosion
North (337.5° – 22.5°)	Moderate
East (22.5° - 157.5°)	High
South (157.5° - 202.2°)	Moderate
West (202.5° - 337.5°)	Low

In this classification, those slopes with dominant east exposition are considered as highly vulnerable to erosion processes because of its conditions of higher solar radiation and potentially more dryer microclimate and eventually, scarce vegetation cover. At the same time, the west-exposed slopes are classified as low vulnerability due to its potential conditions of higher humidity and consequently more vegetation cover and more resistance to the erosive processes. North and south exposition are valuated as moderate vulnerability to erosion processes.

4.3.2.2 Geomorphological processes

Geomorphological processes are natural mechanisms of weathering, erosion and deposition that result in the modification of the superficial materials and landforms at the Earth's surface (Reschlehr et al., 2007; Ryder and Howes, 2008). The most important geomorphological processes in the study areas of this research are erosion and mass movement processes.

Erosional processes involve the erosion of earth materials by either gravity, flowing water, action of wind, or through the chemical solution of rocks (Zhang, 1991; Scherr, 1999; Smaling, 2005). Mass movements are the downslope movements of large masses of superficial material like bedrocks and soil, in which are included landslides, creep and debris flows. These movements are a consequence of the combined action of gravity and internal and external factors (Vargas, 1999; Aguilar and Mendoza, 2002; Beaudry et al., 2006; Davis et al., 2006). Lithology, fracturing, texture or rock strength and slope morphology are considered as some of the internal factors. External factors involve trigger environmental processes such as rainfall, telluric movements and anthropogenic factors such as land uses (Abdallah et al., 2005; Fell et al., 2008; Ryder and Howes, 2008).

Among the different kinds of mass movements, landslides, slumps, rock falls, debris flows and mudflows, are some of the most typical natural hazards in mountain regions, which affect the ecosystems as well as the population and its settlements (De Boer, 1992;

Carrara et al., 1999; Vargas, 1999; Bell and Glade, 2004; Ferrer and Laffaille, 2005; Mora and Keipi, 2006; Alzate et al., 2007). Hence, landslides have traditionally been regarded as key indicators of forest disturbance, particularly in association with logging activities, land use and climatic change or as a response to human-imposed changes such as engineering projects (Vanacker et al., 2003; Claessens, 2007).

4.3.3 Soil

Soil is one of the most important natural resources for mankind. Life on Earth depends on the functions of the soil; they are the basis for both, agricultural production and maintenance of the ecosystems (Pla, 2005). Consequently, soil characteristics are a key piece of the picture of how an ecosystem works. By means of the soil horizon properties, the potential to store water for plants can be derived, as well as the potentiality of the land uses and the location of infrastructure (Levine, 2008). Moreover, soil indicators can be used to evaluate sustainability of land-use and soil management practices in agro ecosystems (Shukla et al., 2006).

Although soil is a vital and largely non-renewable resource (Gobin et al, 2004), it has been severely damaged. Thus, soil degradation which includes deforestation, soil erosion and desertification, has become in a worldwide threat that affects the productivity of all natural ecosystems as well as agricultural, forest, and rangeland ecosystems (Roosee, 1996; Hill et al., 2003; Pimentel, 2006; Smailing, 2008). Therefore, the prevention of soil degradation constitutes a priority within the current actions of environmental planning (Scherr, 1999; GEF, 2003).

Soil erosion is a general phenomenon in the high Andean areas, principally where agriculture is preponderant. These areas suffer progressive reductions of forest cover because the increasing agriculture generates substantial rates of soil erosion (Barrios and Quiñones, 2000; Sánchez et al., 2002). This aspect is treated in this method, considering those features that may orient to determine the soil erosion risk of the study areas. Figure 4.7 presents an overview of some attributes related to the soil degradation processes.

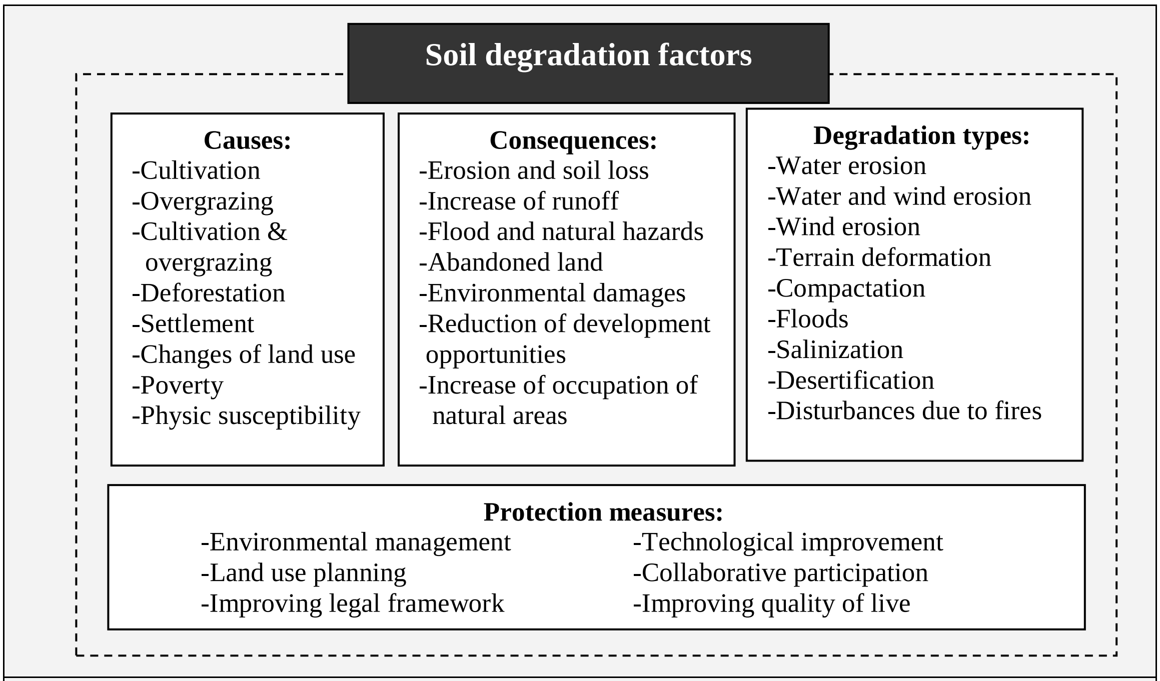


Figure 4.7: Factors associated with soil degradation.

Source: Modified after Stolbovoi and Fischer (1998).

4.3.4 Climate

The analysis of climatic parameters is basic for environmental planning processes, because they are influencing physical and biotic conditions as well as anthropogenic uses. The assessment of the precipitation in rural areas, for example, is related to understanding and explaining hydrological processes on agricultural fields and watersheds due to their impacts on soil erosion and conservation measures (Apaydin et al, 2006). The influence of the climate on the stability of geomorphologic structures, soils and vegetation is recognized. For example, the intensity of the precipitation has a great power of affectation on soils located on steep slopes and environments of sparse vegetation (Martin-Vide, 2004). Additionally, the variability of precipitation over space and time may produce significant hazards, including droughts and floods (Colotti, 1999; Laffaille et al., 2005; Alijani et al., 2008). As an indicator for the climatic condition, the rainfall characteristics of the study areas will be considered for this work.

4.3.4.1 Rainfall

Rainfall is one of the most appropriate forms of precipitation to evaluate climate conditions in tropical regions, especially in areas located below the elevations where hail, sleet or snow could be expected (Gabler et al., 1994). At the same time, rainfall is an important entrance parameter for hydrological analysis of a water basin (Alaghmand et al., 2007).

Besides its importance for agriculture, precipitation is the driving force of the most water erosion processes, through detachment of soil particles and creation of surface runoff (Moore, 1979 cited in Nyssen et al., 2005), but it is also a triggering factor for mass movement and other potentially hazard processes such as floods.

Like most of the climate data, rainfall data are collected using rain gauge stations, hence in specific points of the terrain. Thus, the spatial analysis of this parameter throughout an entire given study area, requires the use of an interpolation method (Earls and Dixon, 2007). For the analysis of the precipitation in this study, data corresponding to climate stations located in and around the study sites have been used. The information was recorded and provided by the Ministry of Environment and Natural Resources and was conformed by annual and monthly precipitation average. Daily precipitation data were not available. For the different cartographic products about climate data the kriging interpolation technique (spatial analyst ArcGis 9.1) was utilized.

4.3.5 Hydrology

Hydrologic systems belong to the most complex dynamic and fragile environments affected both by natural and human factors (Kolditz et al., 2006). Moreover, hydrologic features play a fundamental role in the configuration of the landscapes; therefore it is one of the most useful variables for environmental diagnosis. Thus, for example, the hydrological basin or catchment means a basic reference in the delimitation of territorial units for geographic analysis and environmental management processes.

Hydrology also concerns water quality and quantity. Quantity refers to the available water volume to supply the human and natural systems depending on it, whereas quality refers to the suitability of the water supply for its intended use (e.g., agricultural, domestic, industrial, or natural) (Mustard and Fisher, 2007).

In the analysis of the landscapes it is likewise important to consider the dynamics of the hydrological network, especially in its relation with geomorphologic processes. Thus, precipitation as a fundamental trigger of geomorphologic processes determines the characteristics of runoff and water bodies. Water bodies and runoff represent dynamic environmental features which can be both cause and consequence of the behavior of other environmental components. For example, several land-use types reduce the vegetation cover which limits the percolation and increase the runoff. This can lead to a strong increase in flooding for even quite regular hydrologic events (Verhaeghe and Zondag, 2006).

In this sense, the planning process requires hydro-geomorphological analysis in which will be integrated geographical, geological and hydrological aspects in order to assess the responses of the water bodies to the flow variations and other natural and anthropogenic triggers (Babar, 2006).

In the spatial analysis model proposed in this research, the hydrology aspects are considered by means of the hydrological network, taking into account that the geomorphological action of rivers can be split into bottom (channel) erosion and lateral erosion (bank) (Scheidegger, 1973). Thus, buffer areas were established around the principal streams where are included the zones most likely to be more vulnerable to landslides and floods as a consequence of fluvial dynamics.

4.3.6 Vegetation

Vegetation represents an environmental component to be considered as an indicator influenced by environmental conditions such as climate, altitude, slope aspect or even fauna and anthropogenic uses. Hence, the recognition and analysis of the natural vegetation in comparison with the present one allows at the same time to infer and determine not only the characteristics of the behavior of physical and biotic, but also human factors.

FAO (1995) pointed out the value of the vegetation for maintaining water resources and protecting the soils against degradation; its functions as a regulator of the local and regional climate and of the composition of the atmosphere; its influence on the configuration of habitats for animals and biodiversity; and its value as a protector for crops and cattle against adverse atmospheric influences.

As a result of the complex environmental dynamics, vegetation is also a cause and a consequence of the other environmental conditions and often constitutes one of the first natural resources affected by human interventions. Also, due to geostructural and hydrologic hazards, vegetation may be altered as a consequence of earthquakes, landslides or floods. Global climatic changes are also a latent threat on vegetation and forest ecosystems (Villers and Trejo, 1998; FAO, 2006).

For environmental planning, vegetation has an important function in the control of environmental threats such as soil erosion, because its incidence on the runoff and percolation. Thus, vegetation cover constitutes a protection layer against the erosive impact of the rainfall. In this sense density and type of vegetation are decisive factors in order to allow or control the erosion process.

Vegetation cover is also the basic source of the organic matter content on the top soil, which plays a fundamental role in the control of the soil erosion. With respect to this, Hill and Schütt (2000) state that organic matter influences the physical characteristics of a soil with regard to accelerated soil erosion processes, such as, for example, hydraulic conductivity (percolation and retention of soil water), soil structure (type and size of soil aggregates), and soil color which influences albedo and soil temperature.

Additionally, Van Westen et al. (2008) emphasize the mechanical effect of the vegetation cover on the slopes through the reinforcement of soil by roots, surcharge, wind-loading and surface protection, but also the hydrological effect of removing soil moisture by evapotranspiration and the above mentioned effects on hydraulic conductivity.

In this study vegetation cover will be considered in regard to its contribution to the geostructural stability. Thus, in each study area the characteristics of the different vegetation units in order to establish its potential character as a protector or a facilitator of erosive processes were identified.

4.2.7 Land use

Land use concerns the function or purpose for which land is used by the human population and can be defined as the human activities which are directly related to land, making use of its resources or having an impact on them (FAO, 1995). Since land use is the direct expression of the human intervention on the natural landscapes, it constitutes the main anthropogenic process of the environmental instability. Thus, it is broadly accepted that the intensification of land uses during the last few decades through mining, agriculture, forestry, infrastructure and urbanization, has resulted in degradation of natural resources, especially of vegetation and soils (Pla, 1990; Amler et al., 1999; Sarmiento, 2002; GEF, 2003; Renschler, 2007) which threatens the permanency of the natural resources and reduces the possibilities of wellbeing of the Earth's populations.

Also, in the countryside the inadequate occupation of natural areas especially of those characterized by high sensitivity, causes serious problems (Cohen et al., 2006). There, the changes in land cover and land use resulting from human activities, such as deforestation, forest logging, road construction, fire and cultivation on steep slopes can have direct consequences on landslide activity (Vanacker and Govers 2007; Van Westen et al., 2008;), erosion (Sánchez et al. 2002; Boardman et al., 2003; Ramos et al., 2007; Füsung, et al., 2008) or flooding (GEF, 1999; Sarmiento, 2002).

Additionally, the declination of the soil productivity and its socio-economics impacts belong to the most important consequences of the unbalanced relationship between anthropogenic uses and resources, which is especially evident in Venezuelan rural areas (Sánchez et al., 2002).

However, it is obvious that the different land uses are at the same time indispensables to maintaining human life. In this sense, there is a need to promote that these land uses may be carried out with lower environmental impact and in harmony with the environmental conditions. It is precisely focus of the environmental planning process to reduce the negative effects of the human interventions while enhancing its socioeconomic benefices.

To promote the sustainability of agriculture in rural areas some of the specific land-use strategies should include the following aspects (Sullivan, 2003):

- Keeping the soil covered throughout the year;
- Avoiding moldboard plowing;
- Increasing biodiversity wherever possible through crop rotation, intercropping, use of sod or cover crops, and integrated pest management;
- Applying animal manures or compost; diversifying enterprises and planning for profit;
- Integrating crop and animal enterprises; minimizing tillage, commercial fertilizer, and pesticides;
- Buying supplies locally; employing local people; and
- Including quality of life in your goals

As an important input of the proposed model of spatial analysis, one map of the land use was generated for each study area.

4.3 Methods application

Now that the general structure of the spatial analysis model has been expounded and the various input data have been described, in this section the employed methods in the application of the model are explained.

Figure 4.8 presents a general overview of the technical phases through of which the proposed spatial analysis model was carried out. It is characterized by a sequential decision-making process which involves the following phases: 1) Obtaining of basic information, 2) Digitalization and Rasterization 3) Classification, 4) Layer combinations, 5) Analysis, 6) Interpretation of results. The technical development of the methodology is based on the use of the software ESRI ArcGis (version 9.1) of which the components ArcCatalog and ArcMap were widely used. ArcGIS is a commercial GIS package developed by ESRI. It is one of the most widely used GIS software packages that is able to process and perform analysis on various GIS data formats (Feng and Bajcsy, 2005).

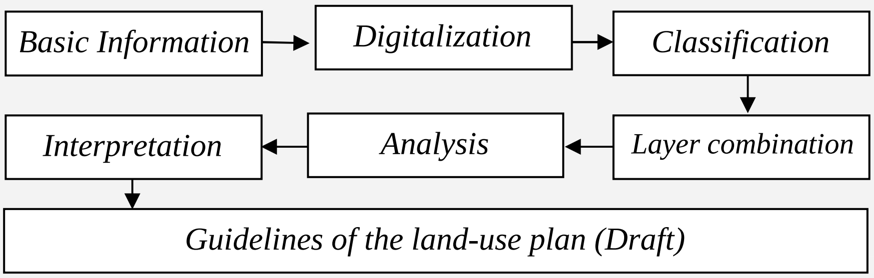


Figure 4.8: Technical phases of the method

Source: Own elaboration

4.3.1 Cartographic scale

The proposed spatial analysis model was carried out by means of a cartographic scale of 1:25.000. In accordance with the objectives of this research and the surface of the study areas, this scale offers a sufficient detail level of detail for an appropriate analysis of the physical and socio-economical features involved in the work. At the same time, by using the indicated scale, a very detailed analysis which could affect the efficient management of the various inputs considered, is avoided. Therefore, the selected detail level of the work allows suitable results to be achieved in order to configure the wished-for guidelines of the sustainable land uses in the study areas.

However, in order to present the elaborated cartography in this publication, the maps were edited in suitable scales. Thus, most of the maps of Rivas Dávila were printed at a scale of about of 1:130.000. The maps of the Quíbor Valley, which has a larger surface than Rivas Dávila, were printed at a scale of about 1:180.000. As reference, a bar with the graphic scale is shown on each map.

4.3.2 Base map

In order to build the base maps of the two study areas, official cartography on a 1:25.000 scale was scanned and then georeferenced in ArcGis 9.1. In the case of Rivas Dávila Municipality the charts 5840-IV-NE, 5840-IV-SE, 5849-IV-SE, 5840-III-NO and 5840-III-SO of the National Cartography of Venezuela were used. For Quíbor Valley, the base map was built from the base map of the project “Hydraulic System Yacambó-Quíbor” elaborated by FUDECO in 1990. Consequently, contours lines each 20 meters (Rivas Dávila) and 50 meters (Quíbor Valley) were digitalized. Boundaries, rivers, roadways, towns and toponyms were also plotted. The elaborated maps (Map 3.2 and 3.10) were the cartographical basis for all subsequent spatial analysis.

4.3.3 Geological analysis

As a basic reference of this environmental component the geological maps, stratigraphic lexicon and the Venezuelan geological code elaborated by institutions as the Ministry of Energy and Petroleum or the national petroleum company PDVSA (http://www.pdvsa.com/lexico/) were used. This information, as well other as the research works carried out by Dugarte (2002), SHYQ (2004) and CIDIAT (2004), was the basis for the analysis of geological faults and lithological conditions of the study areas. Earthquakes were analyzed instead taking into account the earthquake catalogs recorded by public institutions such as Laboratorio de Geofísica - Universidad de Los Andes, Mérida, Venezuela (http://lgula.ciens. ula.ve/), Fundación Venezolana de Investigaciones Sismológicas (http://www.funvisis.org.ve/) and Centro Regional de Sismología para América del Sur (http://www.ceresis.org).

Maps of the earthquakes, which occurred in and around the study areas during the last two centuries, were constructed by means of the digitalization of the earthquake epicenters. The corresponding intensity value, measured according to the Modified Mercalli Intensity Scale (MM), was also considered an attribute which was stored and coded (ID) in an associated database or attribute table.

The Modified Mercalli Intensity Scale (MM) is composed by a system of classification of the earthquakes in 12 levels, expressed in roman numerals (Table 4.3). Thus, as “I” are qualified as those earthquakes that are instrumentally perceived but not felt by persons, unless in favorable conditions. The largest earthquakes are qualified as “XII”, due to the near total damages they cause (Bonilla, 1988; Palme et al., 2005; Ceresis, 2008; Klingand et al., 2008). The elaborated maps are showed in Chapter 5 (Maps 5.1 and 5.19).

Table 4.3: Modified Mercalli intensity scale

Value	Description	Value	Description	Value	Description
I	Instrumental	V	Rather strong	IX	Ruinous
II	Feeble	VI	Strong	X	Disastrous
III	Slight	VII	Very strong	XI	Very disastrous
IV	Moderate	VIII	Destructive	XII	Catastrophic

Source: Ceresis, (2008)

Geological faults were identified by means of the geological maps used as basic reference. Based on these polyline features and their attributes (geological fault and inferred geological fault) a layer was built. Additionally, lithology characteristics were localized and described in accordance with the geological formations referred by the geological maps used as reference. The different geological units were plotted in a polygon shapefile in which the attributes such as name, lithology and geological period were stored in their corresponding attribute table. Other features such as discordances and intrusive contacts were also stored in a third layer. The geological map of the areas that integrate the different obtained layers were shown in Chapter 3 (Maps 3.3 and 3.11). Further analyses of these features are made as part of the application of the model in the Chapter 5.

4.3.4 Relief and geomorphological analysis

Based on the digitalized topographic maps a digital elevation model (DEM) was built for each stuffy area. These DEMs were computed by means of the 3D Analyst tool (Arc-Gis 9.1) with a size cell of 10 by 10 meters. The obtained DEMs were compared with USGS

DEMs, which have a size cell about 92 by 92 meters. These DEMs, provided by Shuttle Radar Topography Mission (SRTM) are freely available on http://srtm.usgs.gov/ (USGS, 2007). Great similarities between the compared topographical DEMs and SRTM DEMs were found, spatially in relation with orientation of slopes and stream network. However, the more detailed topographical DEMs offer notable precisions about the shape of the slopes and the elevation. Thus, taking into account the semi-detailed scale of this work and the relatively small size of the study areas, the more accurate topographical DEMs were selected as basic references for all further analysis. In regard to this Jarvis et al. (2004) affirm that cartography at scales of 1:25.000 and below (i.e., 1:10,000) contains topographic features not captured in the SRTM DEMs.

From these topographical DEMs and by means of the ArcGis 3D Analysis extension, the DEM derivatives slope, aspect (slope orientation) and hill shade were computed. The slope curvature, which estimates the concavity/convexity of the terrain, was also derived from the DEM.

A geomorphological analysis was also carried out. It was based on previous studies executed in the area such as Dugarte (2002) and Ecology and Environment (2004). Aerial image analyses as well as fieldwork were carried out in order to update the bibliographic information. As result, digital layers of the geomorphological characteristics were obtained in which polygons and linear shapefiles stored information about the types of Quaternaries deposits as well as the predominant localization of the geomorphological processes (Maps 3.2 and 3.12). Taking into account the derivatives of DEM, and the geomorphological map a digital layer of the geomorphological units was also built. This layer represents a summarized layer of the relief and geomorphological conditions (Map 5.8 and 5.).

4.3.6. Soil analysis

The utilized soil data was referred to the previous soil maps elaborated for the two analyzed areas. A digital map of the Venezuela soil made by the Ministry of Environment and Natural Resources was used as a reference. Local assessing of the soils realized with several objectives and scales on the study areas were also utilized. Thus, layers of soil class at level of order and sub-order in accordance with the USDA Soil Taxonomy (USDA, 1999) were obtained. By means of them, some soil indicators were deduced and afterwards utilized in the spatial analysis.

4.3.7 Climate analysis

In the conceptual model of spatial analysis, rainfall was defined as an environmental process which, below given conditions, can trigger the environmental instability, e.g. erosion, land slides or floods. Because of this, in this section some approaches and methods are discussed in order to define the most efficient way to involve this parameter in the spatial analysis. The analysis is basically focused on assessing the potential capacity of rainfall to cause or induce erosive processes.

Nine meteorological stations located in and around Rivas Dávila provided monthly and annual average precipitation for the period 1969 - 1998. Between them, the Tovar station has information of mean monthly temperatures. In the case of Quíbor Valley, nine climate stations register data of precipitation (monthly and annual average) for the period 1977 - 2007. Temperature data is provided by four of these stations (Tables 4.3 and 4.5).

Table 4.4: Meteorological stations. Rivas Dávila

Station	*Latitude*	*Longitude*	*Altitude (m.a.s.l.)*	*Mean Annual Precipitation (mm) 1969-98*	*Mean Annual Temperature (°C)*
Bailadores	8°15’10’’	71°49’37’’	1736	691.4	--
La Playa	8°18’29’’	71°46’48’’	1500	718.0	--
La Grita	8°08’50’’	71°59’39’’	1270	738.1	--
Las Tapias	8°13’41’’	71°50’41’’	1920	793.8	--
Pueblo Hondo	8°16’00’’	71°55’00’’	2100	794.9	--
Guaraque	8°08’55’’	71°42’38’’	1710	976.5	--
Tovar	8°20’30’’	71°44’40’’	952	1122.1	21.9
Zea	8°23’22’’	71°46’42’’	900	1248.5	--
Páramo El Quemando	8°14’45’’	71°44’01’’	2212	1538.1	--

Source: MARN (2007)

Table 4.5: Meteorological stations. Quibor Valley

Station	*Latitude*	*Longitude*	*Altitude (m.a.s.l.)*	*Mean Annual Precipitation (mm) 1977-2006*	*Mean Annual Temperature (°C) 1977-2006*
Banco Baragua	10°08’49’’	69°35’31’’	787	394.3	--
Canape	10°01’11’’	69°31’47’’	658	398.2	--
Guadalupe	10°02’29’’	69°40’43’’	582	476.6	25.5
Barquisimeto Ferrocarril	10°04’46’’	69°21’36’’	605	480.5	--
El Tocuyo-Dos Cerritos	9°44’40’’	69°48’25’’	694	394.3	25.5
Quibor	9°55’11’’	69°37’39’’	682	487.9	25.4
San Miguel	9°52’40’’	69°31’03’’	1097	496.6	--
Sanare	9°44’33’’	69°39’24’’	1330	567.4	--
Cubiro	9°47’28’’	69°35’02’’	1097	822.4	19.9

Source: MARN (2007)

4. 3.7.1 Rainfall erosivity

Rainfall erosivity is the potential ability of rainfall to cause soil erosion due to its consequent amount of runoff (Silva, 2002; Rodríguez et al., 1994) and represent a fundamental factor to explain the geomorphologic processes of a territory (Jordan and Bellinfante, 2000).

Erosivity can be quantified by means of the rainfall-runoff erosivity factor (R) of the Revised Universal Soil Loss Equation (RUSLE) and its predecessor Universal Soil Loss Equation (USLE) described in handbooks by Wischmeier and Smith 1965 and 1978 (Renard et al., 1997; Agnese et al., 2006). This calculation is one of the most known indicators of the potential erosion risk (Loureiro and Coutinho, 2001; Silva, 2003).

The erosivity has been defined as a function of the falling raindrop and the rainfall intensity, being the product of kinetic energy of the raindrop and the 30-minute maximum rainfall intensity. This product is known as the erosion index (EI) value. In general, the erosivity is a complex parameter because it links properties of rain, such as quantity and duration of the storm and diameter and velocity of the drops (Colotti, 1999). It has been established that the values of the Erosion Index (EI) give very good correlation for the estimation of soil loss, and is the most reliable estimate of potential rainfall erosivity (Pandey et al., 2007).

Brown and Foster (1978) recommended this equation (1) for calculating unit energy:

$$Ek= 0.29\ [1 – 0.72 \exp (-0.05I_m)] \qquad (1)$$

where ***Ek*** is kinetic energy of 1 mm of rain expressed in MJ/ha**.**mm, while (***i***) is the intensity of the rain expressed in mm/hr. The kinetic energy of a storm depends on the intensities and the amount of precipitation associated with such intensities (Shamshad et al. 2008). Finally, the ***R*** value results in the following equation:

$$R = \frac{\sum_{i-1}^{j} (EI_{30})i}{N} \qquad (2)$$

where ***R*** is rainfall-runoff erosivity factor, ***EI₃₀*** is the value of the kinetic energy for storm ***i*** and ***j*** is the number of storm in an ***N*** year period (Renard et al., 1997; Oñate-Valdivieso, 2004; Pandley et al., 2007).

In many areas of the world it is difficult to estimate the erosivity factor (R) of RUSLE due to the lack of the needed rainfall records (Renard, 1994; Jordan and Bellinfante, 2000) such as hourly and daily rain gauge data. As way to solve the above, some other methods have been wide and successfully used.

Because the intensity data were not available, Thiemann (2006) in his assessment of the soil erosion risk in Ethiopia designed a Rainfall-Intensity Index (RII), which provides a mean to assess the differences in spatial and temporal rainfall intensity. The RII (3) is derived from the quotient of the maximum rainfall totals of one day ($N_{max\ (day)}$) within a month to the rainfall totals of the same month ($N_{(total)}$). This gives a standardized and th~~us~~ comparable value for all meteorological stations and therefore a relatively good indication of the spatial and temporal variation of rainfall intensity (Thiemann, 2006).

$$RII = \frac{N_{max\ (day)}}{\overline{N}_{(total)}}\ [month] \qquad (3)$$

Additionally, two of the most widely known methods to assess rainfall intensity and its correlation with erosivity are the Fournier Index (FI) and the Modified Fournier Index (MFI) (Munka et al., 2007). Considering the rainfall as an important trigger of erosivity, in these two equations a relation between monthly rainfall average and annual rainfall average is established. According to this approach, it is assumed that in the month with the highest rainfall average, the higher erosivity level could be occur.

Fournier Index (4) shows the results of the division between the monthly rainfall averages of the rainiest month (p^2), in the numerator, and the annual average rainfall (P), in the denominator (Silva, 1995; Shamshad, 2008).

$$F = \frac{p^2}{P} \qquad (4)$$

However, Renard and Freimund (1994) suggested the use of the Modified Fournier Index (5), proposed by Arnoldus in 1977, for determining the rainfall erosivity in the regions where the long-term rainfall intensity data is unavailable. Modified Fournier Index (MFI) correlating better than FI with the EI30 (Apaydin et al., 2006; Jordan and Bellinfante, 2000). Apaydin et al. (2006) indicate that the MFI, as a method for assessing the rainfall erosivity, provided basic references to formulate measures to prevent and control the soil erosion.

$$\text{MFI} = \frac{\sum_{i-1}^{12} (Pi)^2}{P} \qquad (5)$$

where, ***MFI*** is the modified Forunier Index value, ***Pi*** is the monthly average precipitation, and **P** is the annual average precipitation. The modified Fournier index offers a much improved relation with R-factor. MFI, similar to the calculated R-factor, increases with increasing rainfall. In contrast, the denominator of the original Fournier Index increases with increased rainfall in the months other than the highest rainfall month. As a result, the Fournier Index can decrease with increasing rainfall, particularly if the rainfall is relatively uniformly distributed throughout the year (Arnoldus, 1977 cited in Renard and Freimund, 1994).

According to Arnoldus (1980) cited in Pascual et al. (2002) and Andrade (2007), the following Table 5.1 below contains a classification of the aggressiveness of the rainfall according to the Modified Fournier Index.

Table 4.6: Aggressiveness of the rainfall according to the Modified Fournier Index Classification

Class	MFI	Description
1	< 60	Very low
2	60 - 90	Low
3	90 - 120	Moderate
4	120 - 160	High
5	> 160	Very high

Source: Arnoldus (1980) cited in Pascual (2001) and Andrade (2007).

Some important works for assessing the rainfall and rainfall erosivity have been carried out in several regions of Venezuela by means of different methods (Páez, 1994; Rodriguez et al., 1994; Barrios and Quiñones, 2000; Silva, 2003; Colotty, 2004; Lozada et al., 2006). In similar areas to those involved in this spatial analysis, Quiñones and Dal Pozzo (2005) and Andrade (2007) carried out assessments of soil degradation by means of the Modified Fournier Index with accurate results.

Due to the indicated advantages offered by this method for assessing the rainfall erosivity in conditions of limited basic information, in the present spatial analysis the Modified Fournier Index will be used to assess the rainfall erosivity.