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# Assessment of Land Use Suitability Based on Water Erosion Susceptibility in Medium-Sized Urban Areas of the Metropolitan Region of Santiago, Central Chile

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# ASSESSMENT OF LAND USE SUITABILITY BASED ON WATER EROSION SUSCEPTIBILITY IN MEDIUM-SIZED URBAN AREAS OF THE METROPOLITAN REGION OF SANTIAGO, CENTRAL CHILE

# ASSESSMENT OF LAND USE SUITABILITY BASED ON WATER EROSION SUSCEPTIBILITY IN MEDIUM-SIZED URBAN AREAS OF THE METROPOLITAN REGION OF SANTIAGO, CENTRAL CHILE

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Arts in Geography

By

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Universidad de Chile
Bachelor of Arts in Geography, 2003

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## ABSTRACT

Urban areas constitute complex spatial entities where biophysical and socioeconomic environments interact through processes that determine the distribution of land use in the territory. Given Chile’s variety of landscapes, water erosion, and mass movement, and rapid expansion of its medium-sized cities, straightforward techniques for assessment of land use suitability are essential. Through evaluation of water erosion susceptibility, it is possible to efficiently determine suitability of land use in medium-sized cities and their adjacent environments. The adaptation and application of the *Erosion Response Units* (ERU) concept (Märker *et al.*, 2001) in the cities of Colina and Melipilla, Metropolitan Region of Santiago, enabled an improved understanding of the relationship among erosion and land use potential variables in urban environments. Since publicly available remote sensor and ancillary GIS data were incorporated, this approach has application beyond the cities studied. The results indicate that it is possible to assess the land use suitability of medium-sized urban areas based on water erosion susceptibility by using an integrated modeling framework. Thus, the highest degrees of land use suitability are associated with lowest degrees of erosion susceptibility.

**KEYWORDS:** land use suitability, medium-sized cities, water erosion susceptibility, Erosion Response Units (ERU)

This thesis is approved for recommendation
to the Graduate Council

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## DEDICATION

This thesis is especially dedicated to my mother Patricia, my sister Loreto, my grandparents Silvia and Julio, and my girlfriend Lynn who are in my heart all the time because they give me the love that I have needed to achieve this academic challenge.

## TABLE OF CONTENTS

# I. INTRODUCTION

An ecosystem is a set of species interacting seamlessly with each other and their environment. Urban areas are not excluded from ecosystems because they are subject to many of the same processes that operate in natural systems. In cities and their surrounding areas, the territory has been transformed and organized to support human survival, and interactions are affected by various landscape processes on the terrain. For this reason, urbanized ecosystems are an ongoing large-scale natural experiment that could be utilized to assess ecological theories empirically (Chiari *et al.*, 2010).

As a manifestation of human intervention in territory land use is important and serves as a generalized descriptor of anthropogenic activities and interactions with the natural environment. In that context, land use planning does not only depend on demographic and economic features, but also on complex combinations of biophysical factors. The end result is a specific form of exploitation of the territory, which is manifested in patterns of occupation within the landscape.

Territorial planning implies that spatial problems are being addressed. It is a technique that provides a model for organizing urban landscapes. Planners will not just develop general guidelines but will aim to improve urban development of specific cities. A systematic, multi-scale evaluation of the impacts of urban land use transition is important, especially for the housing sector (Nuissl *et al.*, 2009). One of the most important aspects of this kind of spatial organization is the evaluation of erosion processes in the urban and peri-urban areas because these can produce a negative impact on the quality of life of urban inhabitants. During recent decades, several studies have revealed the importance of soil erosion in various distinct land use or land cover conditions by soil surveys that provide data on ecological characteristics in urban areas (Martínez-Casasnovas & Sánchez-Bosch, 2000 and Schleufl *et al.*, 1998).

In reality, each model of territorial planning may uniquely describe soil, vegetation cover, topography, and other natural features which influence landscape processes. These in turn affect the how we understand potential runoff and dynamics of sedimentary systems. Regardless of the modeling techniques used, soil erosion is a key factor in some environments, and is not only associated with topographic conditions, but is also controlled by land use and plant cover changes (García-Ruiz, 2010). Some changes in land use may introduce major impacts on biophysical dynamics that at the same time control the spatial organization of humans. Consequently, an early evaluation of geographic features and processes may facilitate planning because this information could be synthesized into an overall environmental strategy that is clearly understood and followed.

Thus, the assessment and determination of water erosion susceptibility in urban environments is necessary in order to develop an accurate plan of optimal land use not only for urban and suburban areas, but also for the landscapes that are part of surrounding watersheds. This is particularly noteworthy in medium-sized cities because these constitute complex spatial mosaics. Therefore, it is essential to apply environmental management and land planning to determine and minimize the impact of erosion in and around such cities.

The procedure used to map soil erosion can be adapted to other situations and may be an effective tool for land use planning (Nicholas & McColl, 1976). In the last twenty years not only have numerous studies identified current erosion, but also to the prediction of future erosion. The concept of *Erosion Response Units (ERU)*, proposed by Märker *et al.* (2001) emerged from the overlap of physical and natural variables for a given area, including a water erosion layer (rill, gully, and some types of mass movements), providing information on the erosive susceptibility.

The objective of this study was to evaluate the susceptibility of terrain to water erosion processes using the ERU concept, and its potential as a tool for identification of land use suitability in the urban environments of the cities of Colina and Melipilla in the Metropolitan Region of Santiago, Chile. Map overlays were used for analyzing and aggregating continuous raster GIS data such as land cover, soil texture, and vegetation. In addition, various factors were evaluated using a multi-criteria scoring system called the Analytical Hierarchy Process (Saaty & Kearns, 1991), as a technique for analyzing complex decisions. These scores assisted in the identification of erosion susceptibility and land use suitability.

Land use planning of medium-sized cities in Chile is rarely practiced. The type of planning demonstrated in this study is important for Chile because of the great variety of environments, ecosystems and water erosion processes in this territory. Urban planning in Central Chile must involve the development of diagnostics to identify the impact of water erosion that occur periodically not only in mountainous areas, but also in the bottom valley.

## II. HYPOTHESIS

This study addressed the following hypothesis: *Assessment of ERU-based water erosion in and surrounding medium-sized cities is an effective approach to their land use suitability due to both environmental impacts as well as the distribution of human activities.*

# III. BACKGROUND AND LITERATURE REVIEW

## Land Use and Land Use Planning Concepts

According to the definition from the Food and Agriculture Organization of the United Nations (2003), land use is characterised by the arrangements, activities and inputs people undertake in a certain type of land cover to produce, change or maintain it. Thus, land use is the representation of the anthropogenic activities that are practiced at a place, such as agricultural or urban uses. This idea of land use differs from the land cover concept because some types of uses are not always associated with physical-natural features.

However, urban land use is one of the key attributes affecting biodiversity around the world and there is an increased interest among ecologists in remnant nature within and around cities. Some ecological effects of urbanization are known including habitat degradation, fragmentation and loss, pollution, and the alteration of biodiversity patterns (Chiari *et al.*, 2010). Therefore, urban land use can produce some cumulative effects on the natural environment on many spatial scales.

Along the same lines, the goal of land use planning is creating the prerequisites to achieve a territory that is sustainable, environmentally compatible, and socially and economically desirable. It is orientated to local conditions in terms of method and content because it considers cultural viewpoints and it is built on local environmental knowledge. Land use planning takes into account traditional strategies for solving issues based on a dialogue between different types of professionals (Amler *et al.*, 1999).

Traditionally there are some aspects of urban planning that designers simply do not consider. For example, many plans focus on the site that they are planning, but rarely consider the situation of ecological issues outside the planning area. In this paradigm, a certain parcel of terrain is either in or out of the study area based on arbitrary boundaries. In another scenario, the design process is created on the assumption that human beings will control the study area in the future (Perlman & Miller, 2005). In reality, natural factors sometimes have the capacity to alter plans even for urban areas.

Nuissl *et al*. (2009) proposed a model of "Driving Forces, Pressure, State, Impact and Response" (DPSIR model) which is widely used in environmental research. It conceptualizes human-environment interaction as the exertion of pressure on the environment, leading to a certain state of the environment that exerts particular impact (Figure 1).

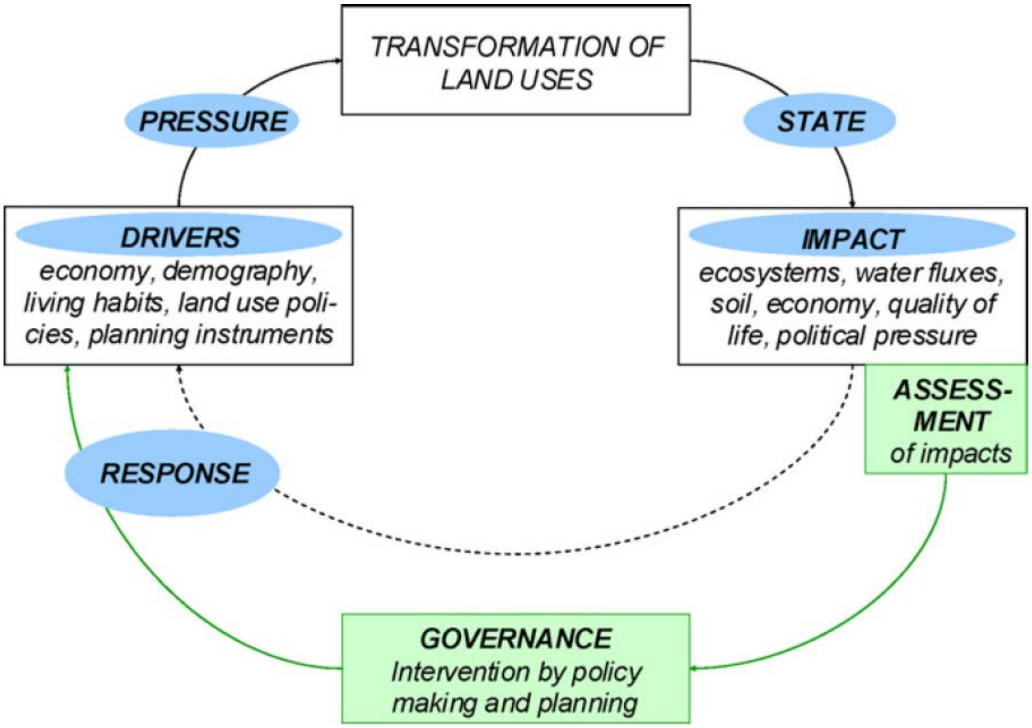


**Figure 1.** Conceptualization of land use transition from Nuissl *et al.* (2009).

## Land Use Suitability

The incorporation of feedback between changing environmental and land use condition is a promising development in land use planning. However, dynamic feedback between the socioeconomic and biophysical components at most only partially in current land use models and in many cases not at all (Veldkamp & Verburg, 2004). In addition, there is much evidence of deficient management of ecosystems where traditional methods do not result in sustainability; as a reaction many approaches are seeking to reduce the impact of traditional resource management (Berkes *et al.*, 2000).

One of the preferred approaches to supporting sustainable land use planning is land evaluation because it aims to compare each potential land use with the properties of individual land units, which are areas that differ from the surrounding land and have homogeneous geographic properties that affect their suitability for different land uses (Van Niekerk, 2010). Nevertheless, the challenges of this process is to prove its importance to the current pressing land use issues because these predictions are only useful if they are used by planners, land users or governments (Rossiter, 1996).

As stated above, a traditional method utilized by planners and researchers for land use suitability assessment is using individual units in homogeneous zones (Figure 2). This method starts with a classification based on layered criteria maps that produce some areas with clustered pixels. After that, the different classes are separated in relation to the discontinuous spatial limits. Next, these sub classes are called zones that are reclassified in new homogenous zones of land use (Joerin *et al.*, 2001).

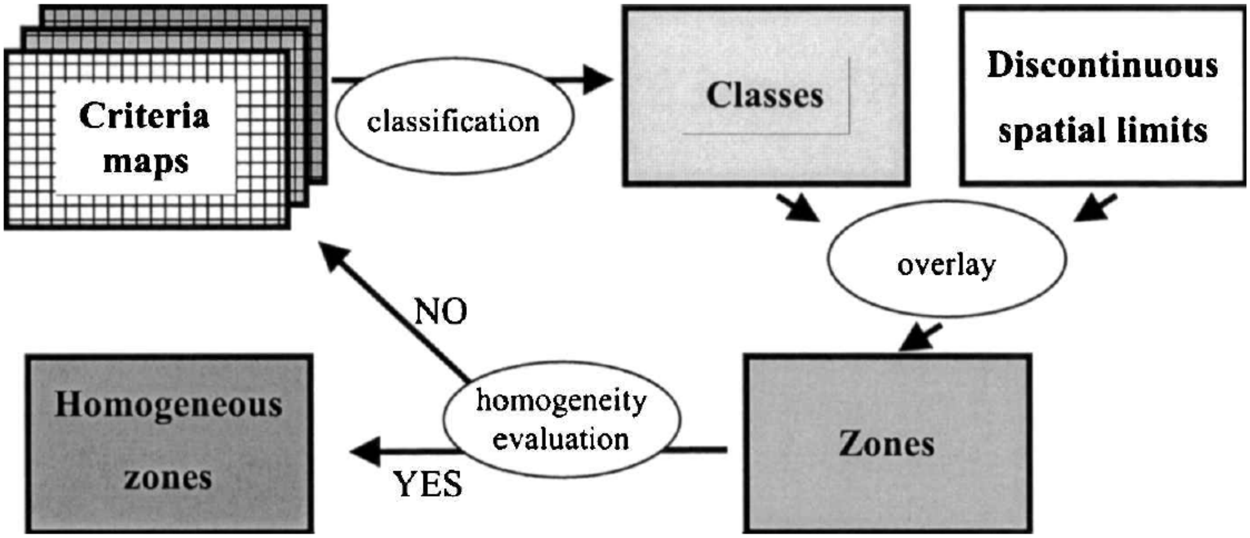


**Figure 2.** Procedure of homogeneous zones (Joerin *et al.*, 2001).

Thus, the land capability or land suitability approach determines the potential to utilize an area of territory for various purposes or management practices (Brown *et al.*, 2008). In other words, the determination of land capability is an important condition for land use planning to proceed on a rational and sustainable basis because it involves assessment and classification of a unit of area according to its suitability for different activities (Kılıç *et al.*, 2003 and Malczewski, 2006).

It is essential that land use planning be compatible with sustainable use, and management sustained productivity of resources and environmental degradation. These aspects assist planners and researchers in ensuring that the territory is used according to its capacity to satisfy human needs. Consequently, it suggests that the land use suitability concept can be defined as the latent capacity of a unit of territory to support natural uses or human activities, due to the spatial configuration of its biophysical and socio-economic components.

In recent decades several approaches to land suitability evaluation have been developed. However, one of the first approaches was developed by the Food and Agriculture Organization of the United Nations (1976), which analyzed suitability based not only on land qualities and water availability, but also on erosion-hazard assessment, which was used as one of the inputs for land suitability classification. Therefore, the determination of land suitability was done mainly by assessing and grouping the land types in orders and classes. The order ranges were from suitable (S), which characterizes land that provides suitability for a specific use and will result in positive benefits, to not suitable (N), which indicates land qualities that are inappropriate for the considered type of use.

According to Ziadat (2007), the accuracy of suitability maps depend on soil attributes, which are used as a basis for making land utilization and management decisions. Thus, in his research in Mafraq City, Jordan, the Ziadat explored the quality of land suitability classifications derived from predicted soil attributes. The research emphasized that the use of soil attributes derived from the prediction model provide an alternative source of soil data in areas where soil maps are not available.

De Baets *et al.* (2009) present a methodology to evaluate the suitability of plants for rill and gully erosion control for semi-arid Mediterranean landscapes. The authors argued that a standard approach to evaluating different types of plants for erosion control strategies is lacking. In their methodology, determination of suitable vegetation for controlling concentrated flow erosion is based on a multicriteria analysis, and it can be applied to other areas suffering from rill and gully erosion.

## Medium-Sized Cities Concept

Worldwide, a large proportion of the urban population lives in small and medium-sized cities, and more than half of that urban population is in urban centers of less than half a million inhabitants, with a sizeable number in towns and administrative areas which have between 5,000 and 100,000 inhabitants (Satterthwaite & Tacoli, 2003).

In Latin America and the Caribbean, the urbanization process that tends to concentrate people in the cities has been intensified in recent decades. For example, between 1972 and 2000 the urban population rose from 176.4 million to 390.8 million, prompted by employed opportunities and better services when compared with rural areas. This level of urbanization puts Latin America and the Caribbean on par with Europe and not far behind the United States and Japan. Additionally, in this region about 47% of the cities' population (35% of the total population) lives in small and medium sized urban areas of less than 500,000 inhabitants (De Vries *et al.*, 2001 and United Nations Population Division, 2001).

According to the evolution of intermediate cities in Chile and Latin America, there is a common criterion for standard sizes in the urbanization process. Urban centers that have between 50,000 and 1,000,000 inhabitants are considered to be medium-sized cities. In fact, in Latin America the intermediate cities are divided into two categories: under 500,000 inhabitants and those between 500,000 and 1,000,000 inhabitants. This is because since the 1950's the smaller group of cities has tended to grow faster than the second category. For example, in Chile, Argentina and Venezuela this difference is striking, is moderate in country such as Mexico and Peru, and practically nonexistent in Colombia (Rodríguez & Villa 1998).

However, trying to delimit the medium-sized city concept using only quantitative criteria would be almost impossible because it is not only defined in terms of demographics and territorial dimensions, but also on the basis of their systemic functions. Thus, it is possible to say that one essential aspect that defines the medium-sized city concept is its role in the mediation of the flow of goods, information, administration, and people, between rural and urban components. Therefore, demographic and spatial sizes are the factors that mostly contribute to the definition of the medium-sized city, but these variables are now considered too rigid and static due to the fact that the level of connection between urban and rural spaces has a great relevance (Bellet & Llop, 2004).

In this context, there are two important elements associated with urbanization: the nature of land use, which is related to what activities are taking place, and the level of territorial accumulation, which shows the intensity and concentration of different land uses. Central zones of cities have a high level of accumulation, while surrounding urban areas have lower levels of accumulation of land use activities (Rodrigue, 2011).

The urbanization process itself occurs as a diffuse growth extending from existing urban zones to rural areas. An important part of the growth might occur in surrounding areas immediately adjoining consolidated urban sectors. Therefore, the rural areas bordering the outer urban area limits are subjected to the pressures of urbanization and industrial development. Rural zones are not only perceived in connection to their current agricultural utilization, but also in terms of their potential urban capabilities (Aguayo *et al.*, 2007). While all of these concepts are associated with the process of spatial expansion and distribution of land uses in medium-sized city environments, such areas produce environmental problems, from minor natural resources degradation to severe constraints on the quality of life and health. Unfortunately, these problems most affect the economically poorest areas of cities (Romero & Vázquez in Robertson, 2007). In these types of cities, there is a continuous process of degradation of the natural environmental and socio-economic-cultural components, manifested in the increased spatial heterogeneity of ecosystems and the increasing levels of socio-spatial differentiation (Romero *et al.*, 2001).

Negative impacts, multidimensional in nature and including the economy, society and natural environment, inevitably accompany the positive contribution of urban areas. In other words, the accumulation of human activities in the cities leads to environmental, social and economic impacts (Bithas & Christofakis, 2006). In medium-sized cities the natural and cultivated vegetation are degraded or eliminated because these surfaces are covered by urbanization. This process involves reducing the green zones and the environmental services they offer such as the regulation of heat islands, groundwater recharge, humidification of the atmosphere, cleaning and recycling of air, and bio-filtration of contaminated soil and water (Romero *et al.*, 2001).

Urbanization is a multidimensional process that not only involves a rapid change in human population density, but also an alteration in land cover (Jorgensen, 2009). Land use planning and environmental assessments are important for medium-sized urban areas because they have more interaction with their surrounding biophysical environments than larger cities, particularly with regard to land use changes on the limits of the intermediate urban areas.

## Water Erosion Process

The processes and forms caused by the action of water are mainly influenced and related to the hydrological dynamics of a drainage basin (Märker *et al.*, 2001). Worldwide, water erosion is the most abrasive type of erosion facilitated not only by environmental deterioration, but also by soil degradation. However, because of climate change, human activities, and changes in rainfall, soil erosion and hydrological processes can intensify, making an accurate prediction of erosion difficult (Wei *et al.*, 2009).

The three main types of surface water erosion by flowing water including interrill, rill, and gully formation, but their mechanisms are different. First, the detachment in interrill erosion is caused and enhanced by rain drop-impact and the soil's intrinsic characteristics. Thus, it depends mainly on rainfall intensity because it occurs when a storm exceeds the capacity of storage of a surface depression, either by a prolonged rain or because rainfall intensity exceeds the infiltration capacity. It is rare that the surface flow is presented as a uniform sheet, but rather it corresponds to a mass of braided streams depression that do not have marked channels (Morgan, 1995 and Wirtz *et al.*, 2011).

Secondly, rill erosion is result from the effect of flowing water exceeding a particular threshold of terrain resistance, by the action of a concentrated flow of water, which occurs on natural hill slopes and on agricultural soils by tillage. Rill erosion is considered to be the most significant process of sediment production worldwide (Bryan, 2000 and Wirtz *et al.*, 2011).

Third, gullies are the relatively continues flows of water produced during rainfall. When this kind of erosion is compared to permanent streams, which are relatively concave in profile, gullies are characterized by falls along its course. They also are deeper and narrower than stable channels and transporting a greater amount of sediments because, over short periods, gullies remove the soil from considerable depths (Morgan, 1995 and Poesen *et al.*, 2003). Along the same lines, Van Zuidam (1985) elaborated a classification of rills and gullies based on depth (cm), and modified by Märker *et al.* (2001) (Figure 3).

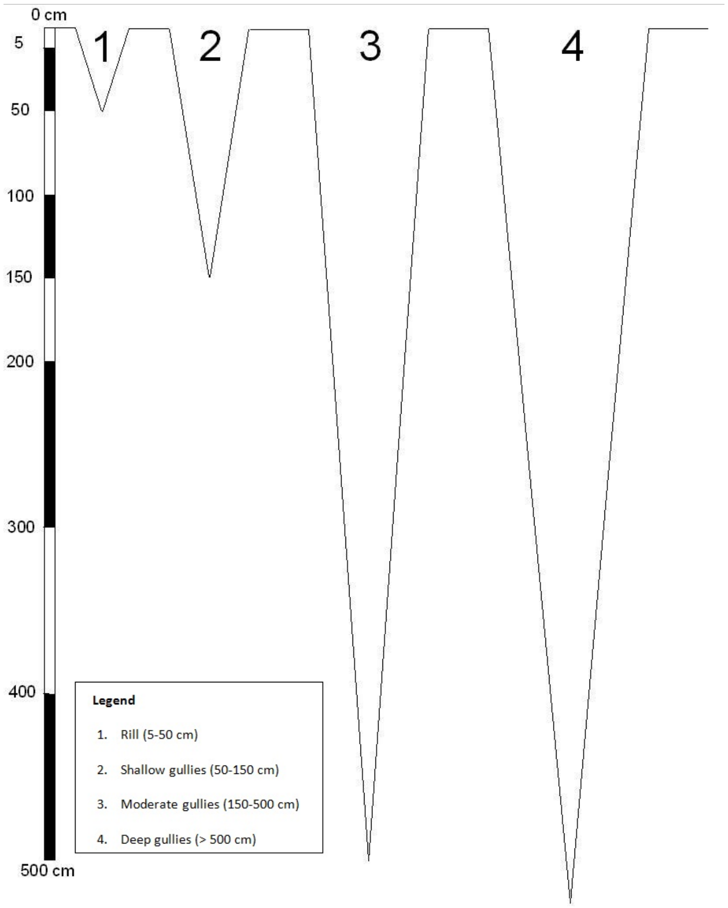


**Figure 3.** Schematic representation of the classification of rills and gullies by depth (cm) elaborated by Van Zuidam (1985) and modified by Märker *et al.* (2001).

However, some types of landslides or mass movements are caused by the action of water. These terms describe a variety of processes which result in the downward and outward movement of slope-forming materials, such as soil, rock, or a combination of these. The different kind of landslides can be classified by the material involved and the type of movement (U.S. Geological Survey, 2004).

The most common two kinds of landslides associated with water action are described as follows. One of them is slides, which are mass movements where there is a distinct area of weakness which separates the slide material from the stable underlying material (Figure 1.4). The next type is the flows, which are mass movements of non-cohesive materials, which occur in soils which are susceptible to loss of resistance, the materials involved temporarily acting as a fluid and undergoing continuous deformation without showing a break defined (Figure 4) (United States Geological Survey, 2004).

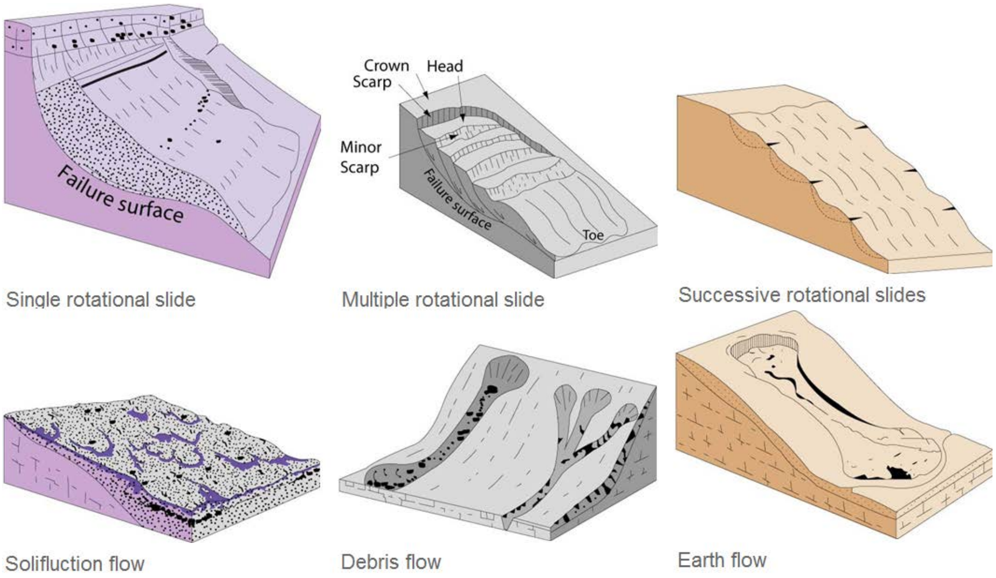


**Figure 4.** Pictures showing various types of slides and flows (British Geological Survey, 2011)

## Terrain Erodibility to Water Degradation

The erodibility of terrain is influenced by different parameters, and it may be associated with the concepts of exposure to degradation of a landscape and its natural resistance to be erodes. In other words, erodibility depends on resistance to erosion, the erosion of the material and its subsequent evacuation (Ferrando, 1992). Consequently, evaluating and analyzing spatial distribution of terrain erodibility is determined as a function of factors including soil resistance to water erosion processes, vegetation cover, land use types, and topographic and geological characteristics.

Along the same lines, because soil erosion potential is increased if the surface has no or very little vegetative cover, vegetation plays an important role as a protective coating. Vegetation protects the soil from raindrop impact and splash, tends to slow down the movement of runoff and allows excess water to infiltrate, which contributes to soil stability. The erosion-reducing effect of vegetation depends on the type, extent and quantity of cover, i.e. forests or permanent grasses (Ministry of Agriculture, Food, and Rural Affairs of Ontario, 2003 and Morgan, 1995).

In addition, land use affects soil properties through the effects of the vegetation cover involved and soil management practices, particularly in the case of agricultural lands. The erosion potential is affected by tillage, depending on the depth, direction and timing of plowing, the type of tillage equipment and the number of passes. Thus, the fewer the disturbances of vegetation over or near the surface, the more effective the tillage practices in reducing erosion (Giovannini *et al.* 2001 and Ministry of Agriculture, Food, and Rural Affairs of Ontario, 2003).

On the other hand, soil erodibility represents the inherent susceptibility of the soil to be degraded by detachment and transport processes triggered by water, and it is one of the factors that affect the likelihood and severity of soil degradation. Soil erodibility is a function of diverse soil properties, such as particle size composition, stability of aggregates, permeability, organic matter content, and chemical composition (Diodato *et al.*, 2011 and Morgan, 1995). In this context, the effect of soil texture greatly modifies the erodibility of soils because it is well known that soil materials that subsurface pore water pressure can significantly modify surface soil losses and erosion rates within rills (Wells *et al*., 2009).

In relation to the lithological factors, differences in erodibility of rocks clearly affect the shape of drainage patterns, which strongly controls the relief and key aspects of the drainage network (Kuhni & Pfiffner, 2001). This important lithologic control on erosion demonstrates that rock strength is relevant for deciphering the effect of topographic indices on the rate of denudation. Factors that determine the mechanical strength of a certain lithology are grain size, degree of cementation and metamorphism, as well as the density and orientation of fractures and joints (Palumbo *et al*., 2009).

However, one of the most important factors of the terrain erodibility is topography, particularly slope. By increasing the slope, erosion increases with the increasing speed and volume of runoff, favoring the displacement of soil particles to lower topographic locations, resulting in a net loss of soil in the highest areas (Morgan, 1995). Flow patterns are determined by the spatial variability of runoff, which are topographic characteristics that determine flow concentration and accumulation of water in the terrain (Vieira & Dabney, 2011).

## Water Erosion Processes in Relation to Land Use

Interactions between elements in the land use system produce hazards not only for society, but also the environment, including soil erosion as a result of deforestation that reduces the surface for forestry and farming. In general, erosion is the source of sediment that fills streams, pollutes water, kills aquatic life, and shortens the useful life of reservoirs (University of Michigan, 2001).

Soil erosion is determined by the absence of protective land cover and sloping areas, whereas sediment exported is determined by on site production and the connectivity of sediment sources, which is also a function of the utilization of territory because transport capacity is different for each type of land use (Van Rompaey *et al.*, 2002). On the other hand, the deintensification of land use commonly implies the transformation from a low protection land cover (e.g. arable land) to a higher protection cover (e.g. grassland or forest), or the regeneration of natural cover. Deintensification of land use might be beneficial in relation to a reduction of on-site soil erosion and sediment export to rivers and lakes (Vanacker *et al.*, 2005).

Globally, water erosion generates negative impacts on agricultural production, infrastructure, and water quality. Regional-scale water erosion evaluation is relevant, but it is limited by data quality and availability. During the past 30 years several studies have been published that fully or partially apply satellite imagery that provides spatial information for assessment of erosion controlling factors, such as soil and vegetation attributes at the scale (Vrieling, 2006).

According to Märker *et al.* (2001), the interaction among soil, vegetation and atmosphere (SVAT interface) acts as an ecosystem where its geographic features control its behavior and determine the erosive response of the terrain (system response). In other words, the ecosystem is stimulated by the relationship between the system of input and the system of characteristics, and it responds in a specific way of erosion (Figure 5).

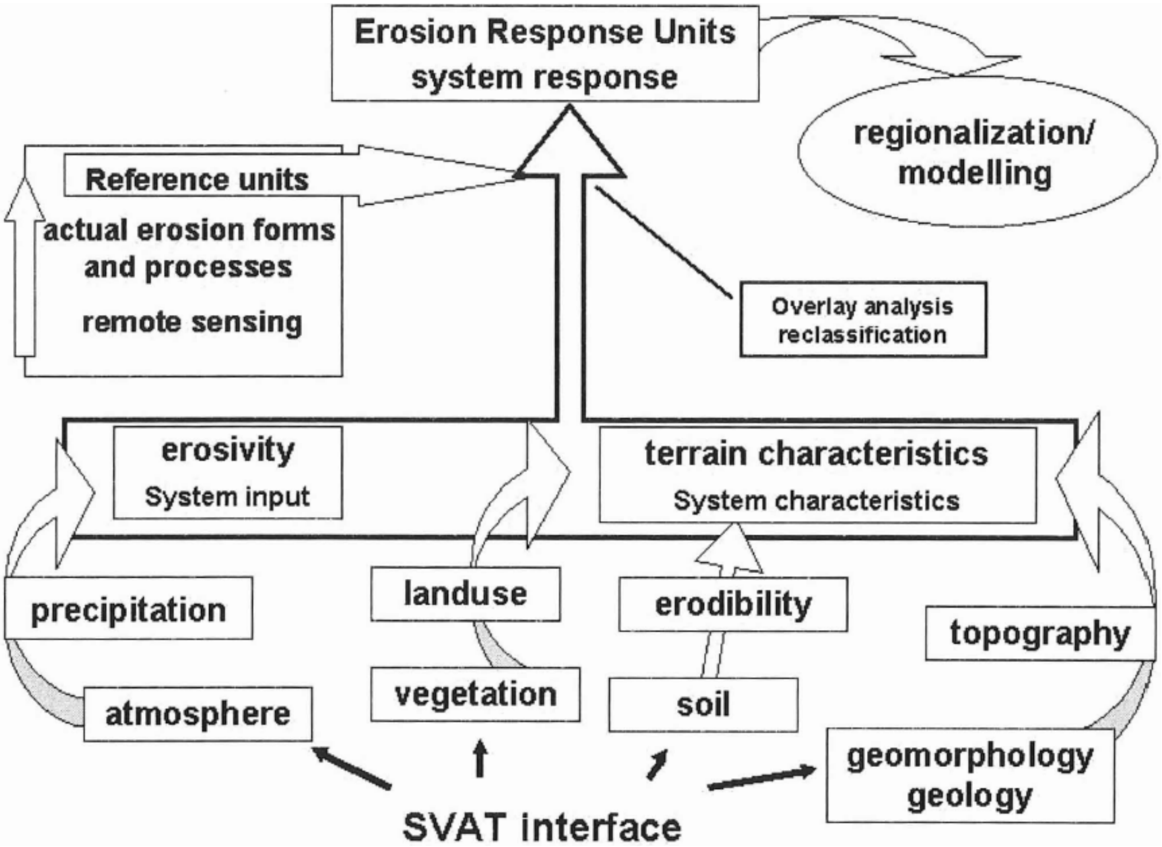


**Figure 5.** Erosion Response Units concept (Märker *et al.*, 2001)

In the scheme of Märker *et al.* (2001), the areas that develop similar erosion processes (system response) and that have the same spatial interaction between inputs (atmosphere) and terrain system (vegetation, land use, topography, soil, and geology), have been designated as *Erosion Response Units* (ERU). One important component for the final delineation of these units is the description of existing water erosion processes, such as rill, gully, and mass movements, by the determination of *Erosion Reference Units* (ERefU). The latter are classified in relation to vegetation cover mostly using remote sensing and GIS.

The spatial patterns of land use change seem to have a relevant impact on the response of soil erosion and sediment export factors (Bakker *et al*., 2008). Landscape processes and land use changes are interrelated and influenced by socio-economic and biophysical factors, resulting in a complex system. Therefore, in areas with active landscape processes such as erosion, land use changes ought to be analyzed accounting for onsite and offsite effects on landscape processes, which is evaluated by performing map overlays comparing the results for the different scenarios (Claessensa *et al.*, 2009).

Soil erosion from cities is by far the largest source of sediment in the runoff of urban areas under development. The erosion of the surface soil is the worst onsite damage in urbanization as it eliminates the soil's ability to regulate water flow. As a result, the eroded soil inundates sedimentation basins in downstream areas (Maniquiz *et al.*, 2009). Sediment affects transport and deposition of soil eroded in downstream rivers and morphological changes in the stream channels (Vanacker *et al.*, 2003). In addition, episodic slope fractures are common in landscapes such as mountains surrounding urban areas. These become an issue when interacting with human activities in which some disasters result in damage and loss of life (Hansens, 1984).

Erosion needs to be identified by maps that show its localization and distribution because it is useful in providing regional and/or national perspectives (Mitra *et al.,* 1998). Nevertheless, these kinds of products are not only important for the determination and study of erosion susceptibility in a particular area, but also for the evaluation and analysis of land use suitability in urban environments. There is a relationship between the factors that determine both geographic phenomena.

## IV. METHODOLOGY

The Analytical Hierarchy Process (AHP) and the concept of Erosion Response Units (ERU) were applied and adapted to evaluate erosion susceptibility in the urban environments of the cities of Colina and Melipilla in the Metropolitan Region of Santiago, Chile. ERU units were used as landscape model entities identifying relative homogeneous water-related erosion processes, and a GIS overlay procedure of weighed data layers was applied to also incorporate present erosion. The procedure is similar to that of Märker *et al.* (2001) which addressed the Mkomazi-river catchment in South Africa through analysis of five parameters (Figure 6). In addition, the level of land use suitability was determined by associating each category of water erosion susceptibility with some types of suitability that were defined by the Food and Agriculture Organization of the United Nations (1976).

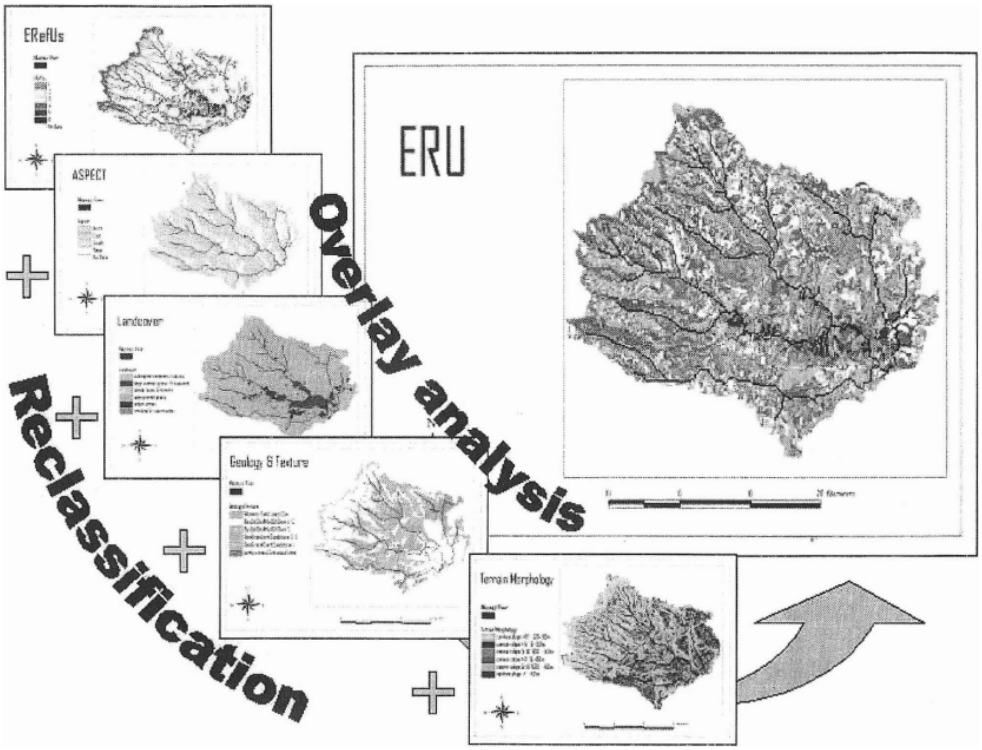


**Figure 6.** Layers used for the ERU delineation for the upper Mkomazi catchment.

## General Features of the Areas of Study

Chile has a special topography and climate not only due to its position adjacent to the Pacific Ocean and Andes Mountains, but also for its long and narrow profile. In Northern Chile it is possible to see the Atacama Desert, which has one of the lowest rainfall totals in the world. The cold and wet southern area of the country is covered with forests, while the coast is a maze of fjords, peninsulas and islands. By contrast, the capital of Chile, called Santiago, lies in a Mediterranean temperate valley and it has dry summers and wet winters (Briney, 2010).

The Metropolitan Region of Santiago of Chile is located between 33° 00’ and 34º 15’ South and between 70º 00’ and 71º 30’ West (Figure 7). It is the most densely populated region in the country. It covers an area of 15,403.2 $km^2$ and there are approximately 6,000,000 habitants. In addition, this regions urbanization is very high at 97%. The Metropolitan Region of Santiago is the main political, industrial, commercial and cultural center of Chile, particularly in the city of Santiago, while the rural areas are more likely characterized by agriculture and mining activities (Gobierno Regional Metropolitano de Santiago *et al.*, 2005).

Overall, the Metropolitan Region has a Mediterranean climate, characterized by a dry season of drought of six to seven months. In relation to its topography, it is noteworthy that over 85% corresponds to mountain systems, 65% of which have slopes greater than 20°. Such systems of mountains correspond to the Andes Mountains (east) and the Chilean Coast Range (west), enclosing the intermediate depression that is a plateau formed by alluvial deposits from the Maipo and Mapocho rivers (Gobierno Regional Metropolitano de Santiago *et al.*, 2005).

**Figure 7.** Locations of cities within Chilean territory (Central Intelligence Agency, 2009 and University of Texas at Austin, 2011)

The study area of the medium-sized city of Colina, which was determined by defining the basin surrounding the urban zone that covers an area of approximately 70 km$^2$, is located 14 kilometers northeast of the metropolitan area of Santiago. Additionally, it is bounded by the UTM coordinates 6,620,000m S and 6,630,000m S and 440,000m E and 448,000m E (Zone 19, Southern Hemisphere). Colina lies in the intermediate depression valley between the Chilean Coast Range and the Andes Mountain Range, at an approximate elevation of 600 meters above sea level, and it is crossed by the Colina River from North to South, which has a low flow and is born at the confluence of several streams in the Andes Mountains (Figure 8 and Figure 9). The weather of the Colina area is warm with a long dry season in summer and rainfall averages 100 mm between April and September. According to the 2002 census, Colina area has a population of 78,000 inhabitants, of whom 63,000 belong to the urban population and 15,000 to the rural population (Municipality of Colina, 2010a).

**Figure 8.** Panoramic view of a residential area of Colina City, flanked by the Andes Mountains (Municipality of Colina, 2010a)

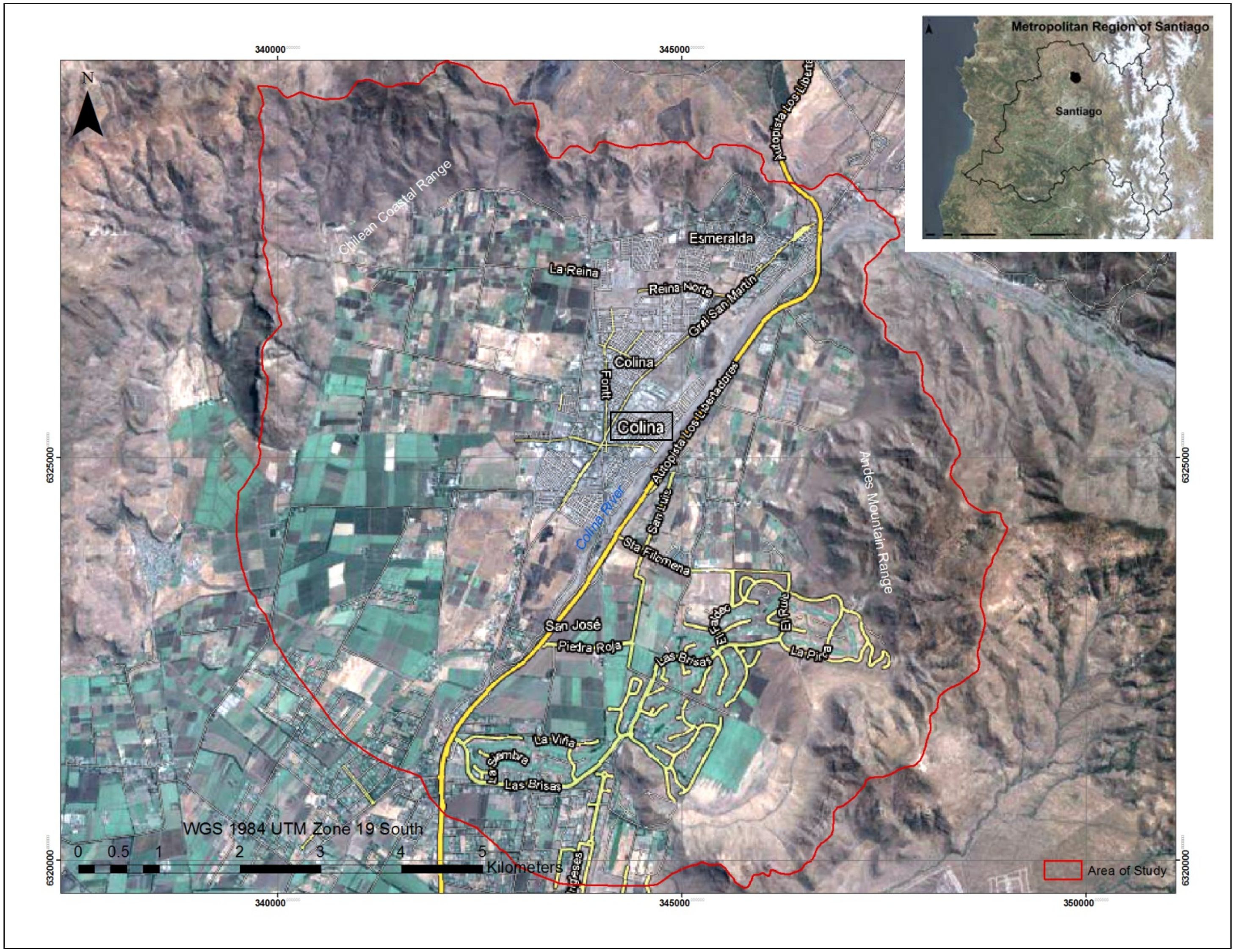


**Figure 9.** Location of Colina City within the Metropolitan Region of Santiago (Google Earth, 2011)

The area of study of the medium-sized city of Melipilla, which was determined by defining the basin surrounding the urban zone that covers an area of approximately 60 km$^2$, is situated on the coastal axis of the Metropolitan Region, about 60 kilometers west of the city of Santiago. In addition, Melipilla is approximately bounded by the UTM coordinates 6,667,000m S and 6,675,000m S and 292,000m E and 302,000m E (Zone 19, Southern Hemisphere). In addition, it is developed in the valleys in the middle of the Coastal Range; Melipilla lies at an approximate elevation of 170 meters above sea level, and it is crossed by the Maipo River, which is the main river flowing through the Metropolitan Region of Santiago (Figure 10 and Figure 11). The study area is classified as a warm temperate climate zone, with a long dry season lasting from seven to eight months. According to the 2002 census, the Melipilla has a population of 98,000 inhabitants, of whom 62,000 belong to the urban population and 36,000 to the rural population (Municipality of Melipilla, 2011).

**Figure 10.** Panoramic view of the south side of Melipilla City in contact with the Chilean Coastal Range (Municipality of Melipilla, 2011)

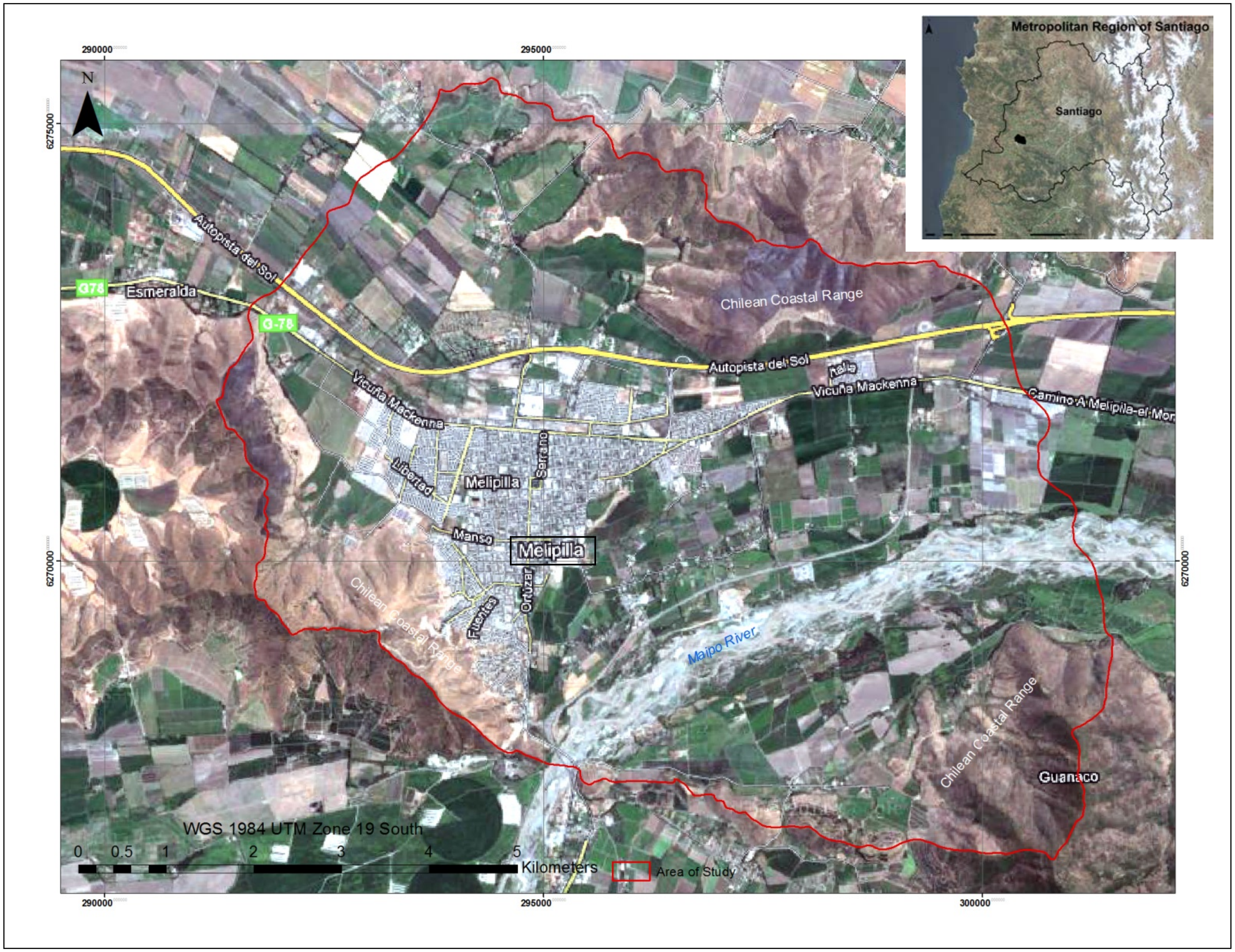


**Figure 11.** Location of Melipilla City within the Metropolitan Region of Santiago (Google Earth, 2011)

## Geographic Data

In order to evaluate the potential use of land based on erosion susceptibility in Colina and Melipilla medium-sized cities, the parameters used by the ERU concept, such as erosion, morphometry, lithology, and soil texture, had to be taken into consideration. Although satellite imagery was used, the majority of the geographic data came from Chilean government agencies (referenced below). In addition, because the study areas were defined at a local level, the scales for the mapping of results were made on that spatial level.

The primary surfaces of geographic data used in this research were in raster and vector format. However, all the data was converted into a grid. First, in order to calculate the Soil-Adjusted Vegetation Index (SAVI), to delineate temporal and spatial variations of vegetation biomass and erosion, it was necessary to obtain a LANDSAT TM scene warehoused by the US Geological Survey (USGS) dated January 31, 2010, with a nominal spatial resolution of 30 x 30 m. These data were downloaded from the Global Landcover Facility (2011) or GLCF developed with support from NASA.

Next, the terrain or morphometric parameter called Stream Power Index (SPI), used to reflect the erosive power of the stream, was obtained using the System of Automated Geoscientific Analysis (SAGA) software, with a nominal spatial resolution of 30 x 30 m, from a Digital Elevation Model (DEM) developed in 2010 by the United States Geological Services (USGS), with a nominal spatial resolution of 30 x 30 m, also downloaded from the Global Landcover Facility (2011).

Third, in relation to the current vegetation types and land uses covering both cities, and their surrounding areas were determined using the governmental geospatial data belonging to the Chilean project called "Ordenamiento Territorial Ambientalmente Sustentable de la Región Metropolitana de Santiago" (OTAS) or "Environmentally Sustainable Land Use Planning in the Metropolitan Region of Santiago." It was focused on an environmental assessment in the Metropolitan Region of Santiago for land management and regional planning, and was published by the Gobierno Regional Metropolitano de Santiago *et al.* (2005). In addition, in order to improve the quality of the data used for land cover analysis, the maps belonging to the regulatory plans of the urban areas, published by the Municipality of Colina (2010b), with a geographic scale of 1:20,000, and Municipality of Melipilla (1988), with a geographic scale of 1:5,000 were used as references.

Fourth, the information on the lithological characteristics of the terrain in the study sites was determined using the lithological formation spatial data from the geologic map of Chile, created and published by the Servicio Nacional de Geología y Minería de Chile (2003) at a geographic scale of 1:1,000,000. This was the result of a multidisciplinary project that collected two decades of geological mapping and scientific data of Chile.

Finally, in order to evaluate the soil texture in the urban environments of the cities of Colina and Melipilla, it was necessary to use the geospatial data from the soil series that is shown in the Agrological Study of Metropolitan Region project, elaborated by the Centro de Información de Recursos Naturales (1996), which is composed of a set of maps of soils with a geographic scale of 1:25,000.

## Conceptual Strategic Models in GIS

GIS processes utilized in this research, and applied to determine the potential land use in the urban environments in the study areas in relation to water erosion process' susceptibility for both medium-sized cities, can be divided into three main parts. This is because a portion of the modeling was conducted with the ArcGIS software, a portion with IDRISI Taiga, and a portion with SAGA GIS.

The first step was the editing of the Landsat TM satellite imagery in the IDRISI Taiga software. One process was the atmospheric correction of the red band (band 3) and the infrared band (band 4) for the satellite scene, using the *Atmosc* tool that corrects remotely sensed images for atmospheric effects with the information acquired from the metadata file which is contained in the imagery. Immediately after that processing, these corrected-bands were used to calculate and determine the Soil-Adjusted Vegetation Index (SAVI), by utilizing the *Vegindex* tool (Figure 12).

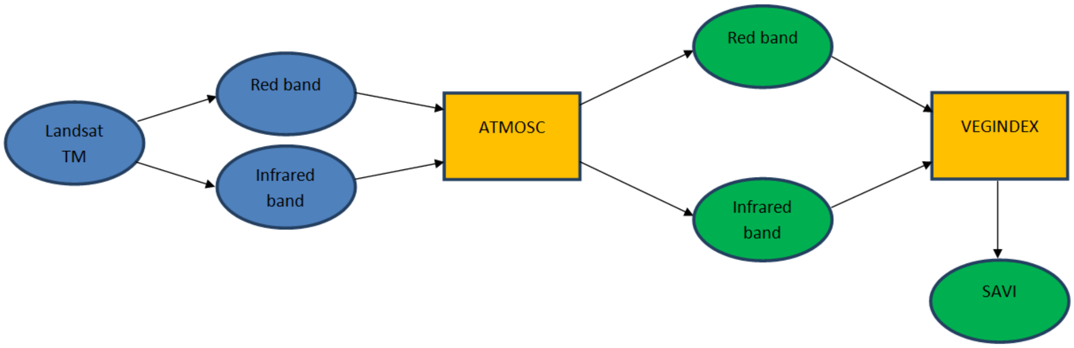


**Figure 12.** Model showing atmospheric correction and determination of Soil-Adjusted Vegetation Index (SAVI) using IDRISI Taiga

The second part was the computation of the Stream Power Index (SPI), which was directly derived from the DEM, developed in 2010 by the United States Geological Services (USGS), using the *Standard Terrain Analysis* tool, belonging to the *Terrain Analysis* module in the SAGA GIS software. This tool generates several raster layers of terrain related data that include some parameters such as slope, aspect, curvature, hill shading, and watershed basins among other surfaces of information, and a single vector layer of the watershed channel network (Figure 13).

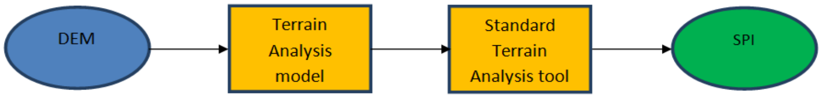


**Figure 13.** The process for the determination of the Stream Power Index (SPI) using SAGA GIS

The third step, conducted in ArcGIS 10, was mostly based on the definition of geographic datum and map projection, conversion of information from vector to raster format, and reclassification and weighing of raster layer data. Thus, using the *Define Projection* tool it was possible to set each data layer on the same coordinate system. Next, another sub-step was the process of transforming the polygon features to a raster dataset by using the *Polygon to Raster* tool. After that conversion, it was necessary to reclassify and changed cell values, using the *Reclassify* tool, not only to process the primary data surface to determine erodibility, but also to identify the water erosion susceptibility and the land use suitability categories. Weighting was the addition of several weighted raster surfaces to determine the ERU values, by using the *AHP* extension and *Weighted Sum* tool (Figure 14).

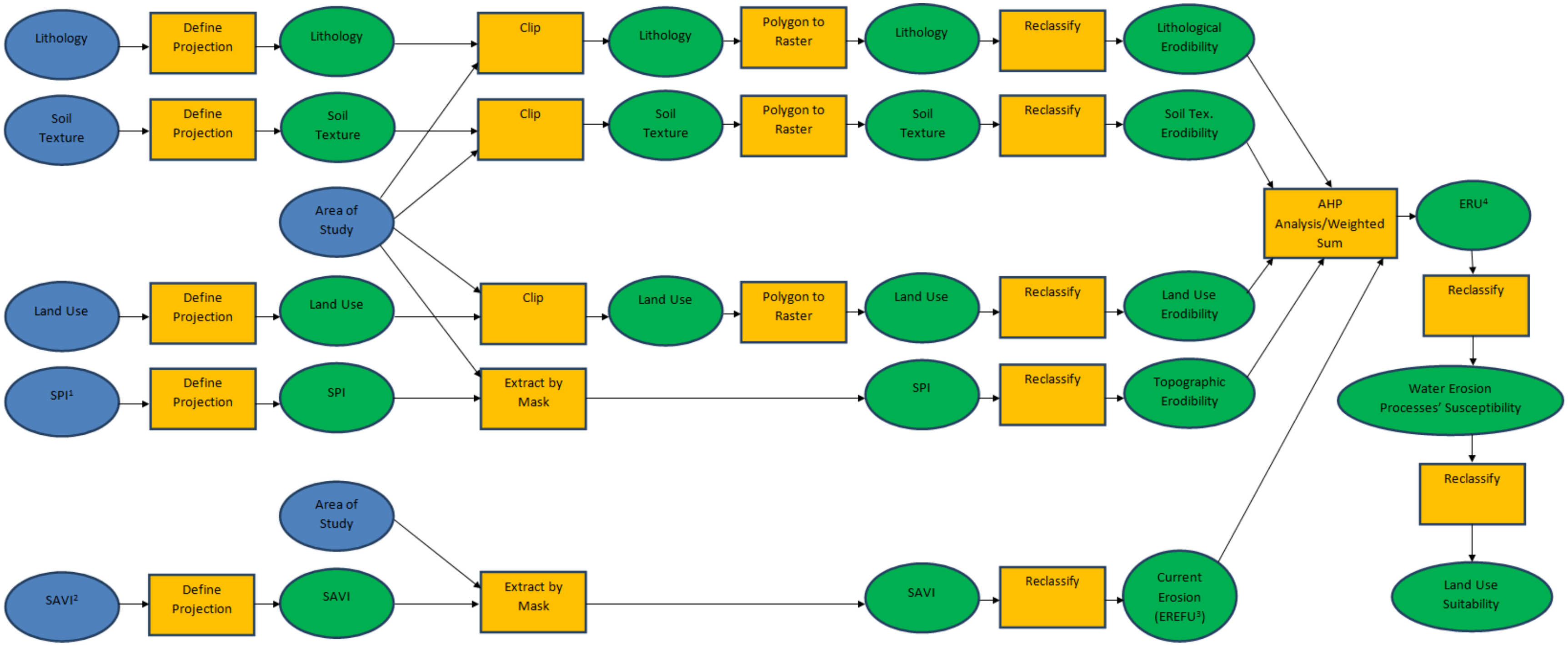


**Figure 14.** Model showing the method used to determine land use potential based on the erosion susceptibility in software ArcGIS

*[1] Stream Power Index, [2] Soil-Adjusted Vegetation Index, [3] Erosion Reference Units, and [4] Erosion Response Units*

## Preprocessing of the Satellite Data

An integral part of this research project was its capacity to utilize an organized approach for pre-editing and processing the satellite imagery acquired for the study areas of Colina and Melipilla before it had been used as an input of information not only in the IDRISI Taiga software, but also in the ArcGIS software. In other words, any satellite imagery into a GIS model required some kind of editing for further processing and utilization in geographic issues.

The remote sensing data used in this research corresponded to the red band (band 3) and the infrared band (band 4), derived from the Landsat TM January 2010, which were corrected by the *Atmosc* tool using the IDRISI Taiga software to retrieve the surface reflectance from imagery by removing the effects produced by the atmosphere. The following equation shows the mathematical processing for the correction, where $\rho_{Pixel,Band}$ is the reflectance for each pixel, for each band; $d_{ES}$ is the sun-earth distance; $Esun_{Band}$ is the spectral solar irradiance; and $\theta_S$ is the solar zenith angle (Chávez, 1996):

$$\rho_{Pixel,Band} = \frac{L_{Pixel,Band} \times d_{ES^2} \times \pi}{Esun_{Band} \times \cos(\theta_S)}$$

Thus, these red and infrared bands, obtained from the Landsat TM imagery, were corrected for the atmospheric effects by using the Cos(t) model, which is an improvement of the Dark-object Atmospheric Correction model that is applied to Landsat 5 TM multispectral data with bands 1-5 and 7. The input image file is assumed to have only these 6 bands for the processing (Chávez, 1996).

Later, the SAVI was calculated by the *Vegindex* tool in the IDRISI software using the red band (band 3) and infrared band (band 4), assuming that healthy vegetation absorbs most of the visible light and reflects a large portion of the near-infrared light. This index is an improvement of the Normalized Difference Vegetation Index (NDVI) used to determined vegetation cover, biomass, and leaf area index (Outtara *et al.*, 2009). The SAVI is represented by the following equation, where *L* is the incorporation of a soil factor correction (value 0.5) into the NDVI equation (Qi *et al.* (1995) in Jensen, 2007):

$$\mathrm{SAVI} = \frac{NIR - red}{NIR + red + L} * (1 + L)$$

**Preprocessing of the Topographic Data**

In the model used by Märker *et al.* (2001), one relevant factor was the topography, including slope gradient, slope length and curvature. However, in this project the SPI was just used in order to have an integral evaluation of the terrain, processing and editing by the *Standard Terrain Analysis* tool in the SAGA GIS software. It is utilized to reflect the erosive power of streams based on the assumption that the denudation of water increases proportionally with an increase in the catchment area, which is the function of the product of flow accumulation and slope (Hrvatin *et al.*, 2006). Since a number cannot be divided by zero, all zeros must be eliminated from the data set in this index. It is done by adding 0.001 to all information layers in the calculation that can be represented by the following equation (Center for Advanced Spatial Technologies, 2010):

$$\mathrm{Ln}(([\mathrm{FlowAcc}] + .001) * ([\mathrm{Slope}] + .001))$$

## Setting and Editing of the Geographic Data

Editing is an essential step for managing, analyzing and displaying geographic information**.** Thereby, in order to set the primary surface of geo-data for determining land use potential based on the erosion susceptibility, it was necessary that each layer was set in the same map coordinate system. Not only the Universal Transverse Mercator (UTM) Zone 19 South projection, but also the World Geodetic System (WGS) 1984 datum was specified using the *Define Projection* tool in the ArcGIS software. This step is not only useful if the input dataset does not have a projection defined, but also is helpful if the feature class's projection parameters are unknown or incorrectly specified (ESRI, 2007).

The next editing stage was sectoring the areas of the project based on water parting criteria. It was done using two types of processes in the ArcGIS software that pick up the data that corresponded to the area defined. Thus, one of them was the *Clip* tool for vector data layers, such as land cover, lithology, and soil texture, which extracts existing data by using a polygon shapefile as a reference. The other was the *Extract by Mask* tool for SAVI and SPI layers, which removes the cells of a raster that correspond to the areas defined by a mold (ArcGIS, 2007).

Each vector data set was transformed to raster format in a nominal spatial resolution of 30 x 30 m, using the *Polygon to Raster* tool in the ArcGIS software. This processing converts a polygon shapefile into a raster format, for advanced spatial assessment and environmental management, by using a raster file as an input feature as a reference model that determines the cell size in the output raster dataset that was created (Olivera & Koka, 2003).

## Reclassification of Geographic Data and Assessment of Erodibility

The reclassification of the primary surface of geo-data into the secondary surface of information was done using the *Reclassify* tool in the ArcGIS software. In this study, it was used to recognize not only the different levels of susceptibility of erosion in each raster data layer, but also the types of the current water erosion on the terrain (ERefU). It is a useful tool when researchers and professional map makers want to replace the values in the input raster data set into a new category of reclassified values by the creation of an output raster layer (ArcGIS, 2007).

First of all, to perform an analysis of the spatial distribution of vegetation, in order to determine the current water erosion processes, based on the adaptation of the ERefU concept from Märker *et al.* (2001), SAVI values were reclassified into five categories of vegetal biomass, which are associated with current erosion types, using a basic statistical thresholding method, where $\sigma$ is standard deviation and $\bar{X}$ is the mean (Table 1):

Table 1. Vegetation biomass and current water erosion category

| SAVI threshold | Biomass category | Current erosion (ERefU category) | Erosion type |
|---|---|---|---|
| $> 2\sigma$ | Very high | Very slight | Interrill |
| Between $1\sigma$ to $2\sigma$ | High | Slight | Rill and interrill |
| Between $\bar{X}$ to $1\sigma$ | Medium | Moderate | Rill and gully |
| Between $-1\sigma$ to $\bar{X}$ | Low | Severe | Gully and landslides |
| $< -1\sigma$ | Very low | Very severe | Gully and sever mass movements |

**Source:** After Märker *et al.* (2001)

Secondly, SPI numbers were reclassified into five categories using the criteria that were elaborated by Hrvatin *et al.* (2006) in order to determine topographic erodibility. Thus, high SPI values show areas of both upper slopes and high flow accumulation in the terrain. In other words, high SPI numbers represent a greater potential for erosion risk. On the other hand, low SPI numbers represent areas of soft slope and low levels of flow accumulation in the surface, which is interpreted as a lower erodibility (Table 2).

Table 2. Stream Power Index (SPI) category

| SPI threshold | General description | Erodibility |
|---|---|---|
| ≥ 2,000 | Very high slope and flow accumulation | Very strong |
| Between 1,000 and 1,999 | High slope and flow accumulation | Strong |
| Between 100 and 999 | Moderate slope and flow accumulation | Moderate |
| Between 10 and 99 | Low slope and flow accumulation | Weak |
| Between 0 and 9 | Very low slope and flow accumulation | Very weak |

**Source:** Based on Hrvatin *et al.* (2006)

Next, in order to describe the water erosion processes and potential land utilization, land use in the project areas of the mid-sized urban areas had to be taken into consideration. Thereby, another stage of this research was to create and edit a layer of existing land uses and cover in the terrain, using data from a set of information documented by the OTAS project (Gobierno Regional Metropolitano de Santiago *et al.* (2005). Consequently, based on the criteria of Märker *et al.* (2001) and Platt & Rapoza (2008), the following six categories of land uses, and four of erodibility, were determined (Table 3).

Table 3. Land use category

| Category | General description | Erodibility |
|---|---|---|
| Riverbed | Stream bank | Very strong |
| Industrial/transport | Industrial, military, and road Infrastructure | Strong |
| Residential | Single or multifamily housing | Strong |
| Cultivated | Cropland and pasture | Moderate |
| Bushland/prairies | Opened canopy of bushes or grassland | Moderate |
| Bushland | Closed canopy of bushes | Weak |

**Source:** After Märker *et al.* (2001) and Platt & Rapoza (2008)

Fourth, superficial soil texture controls the soil susceptibility of erosion. Along the same lines, soils high in silt and very fine sand tend to have high erodibility because they show low cohesion force and are more prone to transportation, but erodibility is low for soils abundant in clay (ÓGeen *et al.*, 2006 and Aba Idah *et al.*, 2008 in Neyshabouri *et al.*, 2011). Therefore, the following five categories of soil texture are erodibility were classified (Table 4).

Table 4. Superficial soil texture category

| Category | General description | Erodibility |
|---|---|---|
| Fluvial material | Gravel, boulder, and sand | Very strong |
| Sandy loam | Approx. 10% of clay and 70% of sand | Strong |
| Loam | Approx. 20% of clay and 40% of sand | Moderate |
| Clay loam | Between 30% and 40% of clay | Weak |
| Clay | ≥ 55% of clay | Very weak |

***Source:*** After Neyshabouri *et al.* (2011)

Finally, one of the most relevant parameters was lithology because this feature shows the types of rocks in the terrain, using the data from the Servicio Nacional de Geología y Minería de Chile (2003). The reclassification of the lithological units was based on criteria designed by Kuhni & Pfiffner (2001) for the Swiss Alps, used to examine the relationship between the hydrology and formation of the mountains. Thus, the lithological levels of erodibility descend from sedimentary to intrusive rocks, reclassified into four categories (Table 5).

Table 5. Lithology category

| Category | General description | Erodibility |
|---|---|---|
| Alluvial sediments | Gravel and fine material | Strong |
| Colluvial sediments | Mainly gravel | Moderate |
| Extrusive igneous rocks | Volcanic igneous rocks | Weak |
| Intrusive igneous rocks | Rocks from molten earth material | Very Weak |

**Source:** After Kuhni & Pfiffner (2001)

## Multivariate Analysis of Geographic Data

The third level of information in this research corresponded with the surfaces of geo-data derived from the secondary surface of information created by reclassification. Thus, each category in every layer was weighed in relation to the level of susceptibility of erosion. This was done using the Analytic Hierarchy Process (AHP), which according to Saaty & Kearns (1991), is a procedure used to represent a problem hierarchically. It is a rational, efficient and organized graphical system, clearly stating the objective pursued as well as the variables and decision criteria considered, using a hierarchical model (Figure 15).

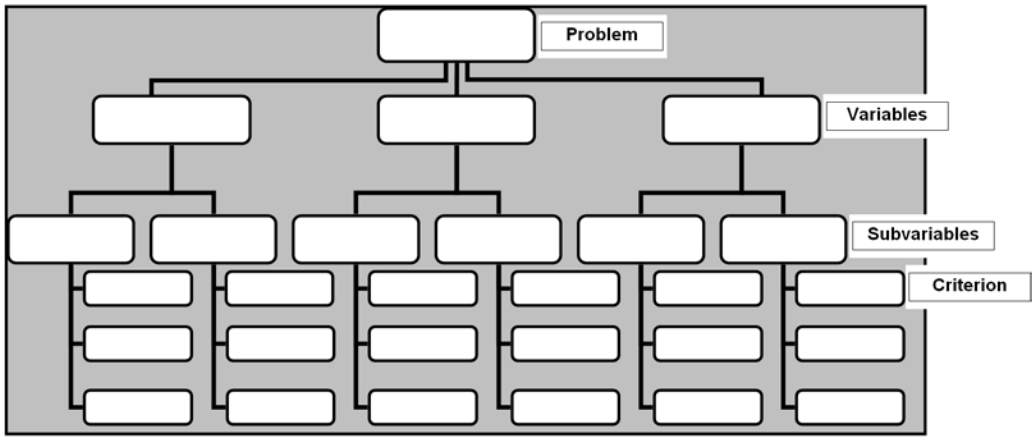


**Figure 15.** Analytic Hierarchy Process (Saaty & Kearns, 1991)

Thus, it was necessary to weigh the component parts, determining the relative importance each element has on the total value or percentages of the problem, through the contrasting of the pairs of elements by a matrix of pairwise comparison, using the *AHP* extension in the ArcGIS software. In other words, it was making a contrast among every reclassified layer with respect to their relevance for the susceptibility to erosion (Table 6), based on the scale of importance proposed by Saaty & Kearns (1991) (Table 7).

Table 6. Peer comparison matrix

| | ERefU | Topography | Land use | Soil texture | Lithology |
|---|---|---|---|---|---|
| ERefU | ERefU/ERefU | T/ ERefU | LU/ERefU | ST/ERefU | L/ERefU |
| Topography | ERefU/T | T/T | LU/T | ST/T | L/T |
| Land use | ERefU/LU | T/LU | LU/LU | ST/LU | L/LU |
| Soil texture | ERefU/ST | T/ST | LU/ST | ST/ST | L/ST |
| Lithology | ERefU/L | T/L | LU/L | ST/L | L/L |

**Source:** Based on Saaty & Kearns (1991)

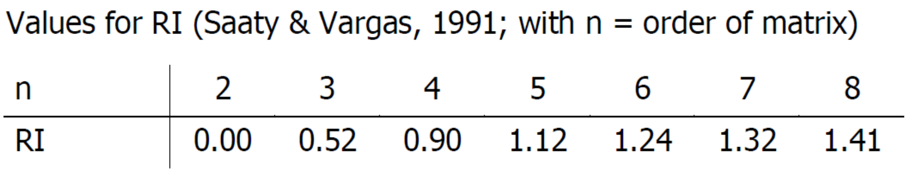
Table 7. Scale of importance

| Importance (numeric scale) | Definition (verbal scale) |
|---|---|
| 1 | Both elements have the same importance |
| 3 | Moderate importance of an element over another |
| 5 | Strong importance of an element over another |
| 7 | Very strong importance of an element over another |
| 9 | Extreme importance of an element over another |
| 2, 4, 6, 8 | Value intermissions between two adjacent trials |
| 1/2, 1/3,1/4, etc. | Reciprocals or values for inverse comparison |

**Source:** Saaty & Kearns (1991)

Saaty & Kearns (1991) provided the Consistency Ratio (CR), which is a value calculated to check for the logical consistency of a pairwise comparison matrix. Thus, when CR=0.0, there is no inconsistency among the pairwise comparison judgments, or the judgment is considered 100% consistent. As the value of CR grows, the degree of inconsistency is also considered to grow. A review of the preference matrix is recommended if the consistency ratio CR exceeds a value of 0.1. It is defined as the ratio of the Consistency Index (CI) to an average consistency index Ratio Index (RI), thus it is represented by the following equation:

$$\mathrm{CR} = \frac{CI}{RI}$$



Values for RI (Saaty & Vargas, 1991; with n = order of matrix)

| n | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| RI | 0.00 | 0.52 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 |

$$CI = \frac{\lambda_{\max} - n}{n-1}$$

where

$\lambda_{max}$: greatest eigenvalue of preference matrix

n: order of matrix

When all the parameters or variables and their categories of erodibility were weighed, these percentages were combined to determine the ERU, which are the sum of all the weighted layers. It was done by the *Weighted Sum* tool, which provides the ability to add all input raster data together to create an output raster (ArcGIS, 2007). For this reason, the ERU correspond to the present erosion and contain a particular combination of parameters, which influences the erosion response in each unit of the terrain.

## Water Erosion Susceptibility and Land Use Suitability

Next, this multivariate classification analysis for determining the ERU units in the study areas was used as a source for this research. Consequently, the following five categories of water erosion processes' susceptibility were reclassified from the ERU data, from very weak to very strong categories, using a basic statistical thresholding method, where $\sigma$ is standard deviation, by utilizing the *Reclassify* tool in the ArcGIS software (Table 8).

The last stage was the determination of the land use suitability by the association of each water erosion susceptibility category with a type of land suitability for the urban environments of the cities of Colina and Melipilla. Thereby, the categories of the susceptibility of water erosion were reclassified into six new classes, from not suitable to highly suitable, based on an adaptation of the classification defined by the Food and Agriculture Organization of the United Nations (1976), which considers erosion conditions as a layer of information in the evaluation processing of suitability (Table 8).

Table 8. Water erosion processes' susceptibility and land use suitability category

| ERUs threshold | Erosion susceptibility | Land use suitability | General description |
|---|---|---|---|
| $> 1^{1/2} \sigma$ | Very strong | Not suitable | Land that cannot support some types of uses on a sustained basis |
| Between -½ to ½ σ | Strong | Marginally suitable | Land with limitations so severe that benefits are reduced |
| Between $-1^{1/2}$ to -½ σ | Moderate | Moderately suitable | Land that is clearly suitable but which has limitations |
| Between $-2^{1/2}$ to $-1^{1/2} \sigma$ | Weak | Suitable | Land without significant limitations |
| $< -2^{1/2} \sigma$ | Very Weak | Highly suitable | Land that can support different land uses |

**Source:** After the Food and Agriculture Organization of the United Nations (1976) and Märker *et al.* (2001)

### Pearson Correlation Coefficient

An additional statistical processing determined not only the relationships between erodibility from four of the factors, but also quantitatively tested the erosion susceptibility and land use suitability results with current erosion data (based on the SAVI). For this reason, the Pearson's R statistical correlation was used, by the *Regress* tool in the IDRISI software, which is a measure of the strength of a linear association between two variables and is indicated by *r*. The Pearson correlation attempts to draw a line of best fit through the data of two variables, and it shows how far away all these data points are to this line of best fit (Laerd Statistics, 2011).

The equation to calculate $r$ in order to examine the correlation between two variables, $x$ and $y$, which have a normal distribution and standard deviations, $s_x$ and $s_y$, where $n$ is the number of observations, is (Kalogirou, 2011):

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Laerd Statistics (2011) has proposed guidelines to interpret Pearson's correlation coefficient (Table 9).

Table 9. Guidelines for the interpretation of Pearson's correlation coefficient

| | Coefficient, *r* | |
|---|---|---|
| Strength of association | Positive | Negative |
| Weak | 0.1 to 0.3 | -0.1 to -0.3 |
| Moderate | 0.3 to 0.5 | -0.3 to -0.5 |
| Strong | 0.5 to 1.0 | -0.5 to -1.0 |

**Source:** Laerd Statistics (2011)

## V. RESULTS

### Vegetation and Erosion

The distribution of vegetation and different erosion types and their intensities was provided for the study areas with classes of present erosion, ERefU, using LANDSAT TM scene analysis. The SAVI values in the catchment surrounding Colina ranged between -0.078 and 0.767, with a mean and standard deviation of 0.231 and 0.138 respectively, indicating that plant distribution is very heterogeneous with some sectors having extended coverage and others having low coverage. From a detailed spatial analysis, it can be seen that values close to the maximum SAVI numbers are mainly located in the southern area of the intermediate depression valley, indicating a higher vegetation density compared to areas located on the mountains and urban sectors around the Colina riverbed, which have negative SAVI values (Figure 16).

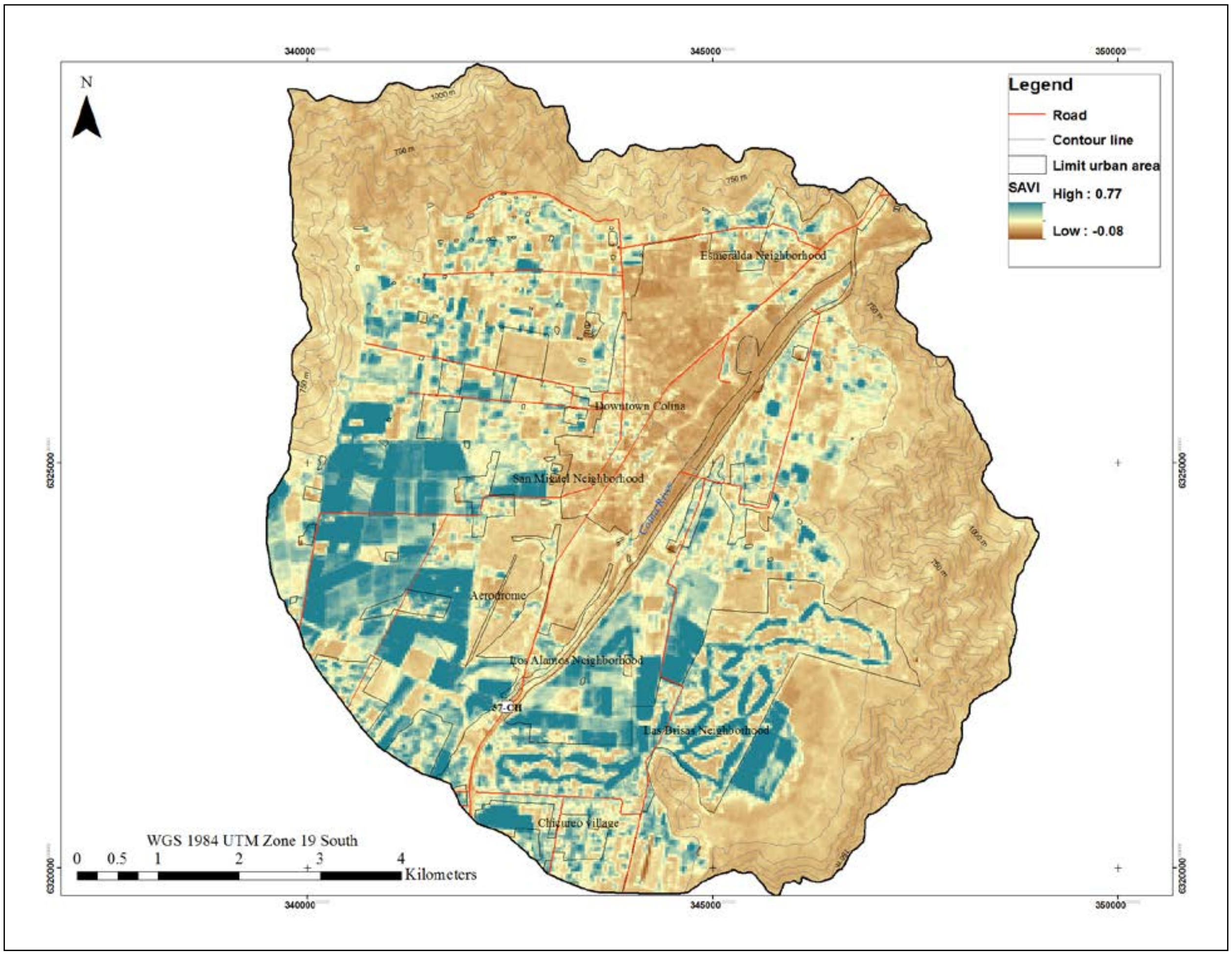


**Figure 16.** Map showing the SAVI values of the catchment surrounding Colina City

In relation to the catchment surrounding Melipilla, the SAVI values ranged -0.505 and 0.808, with a mean and standard deviation of 0.309 and 0.168 respectively, showing that vegetation distribution is very heterogeneous with areas of low density and others with great vegetal density (Figure 17). Thereby, it appears to have a similar spatial pattern to the Colina urban environment because the highest SAVI values are located at the bottom of the valley not only around the Maipo River, but also in the northwestern sector. On the other hand, the negative SAVI values correspond to steeper areas in the mountains and the urban areas of Melipilla city.

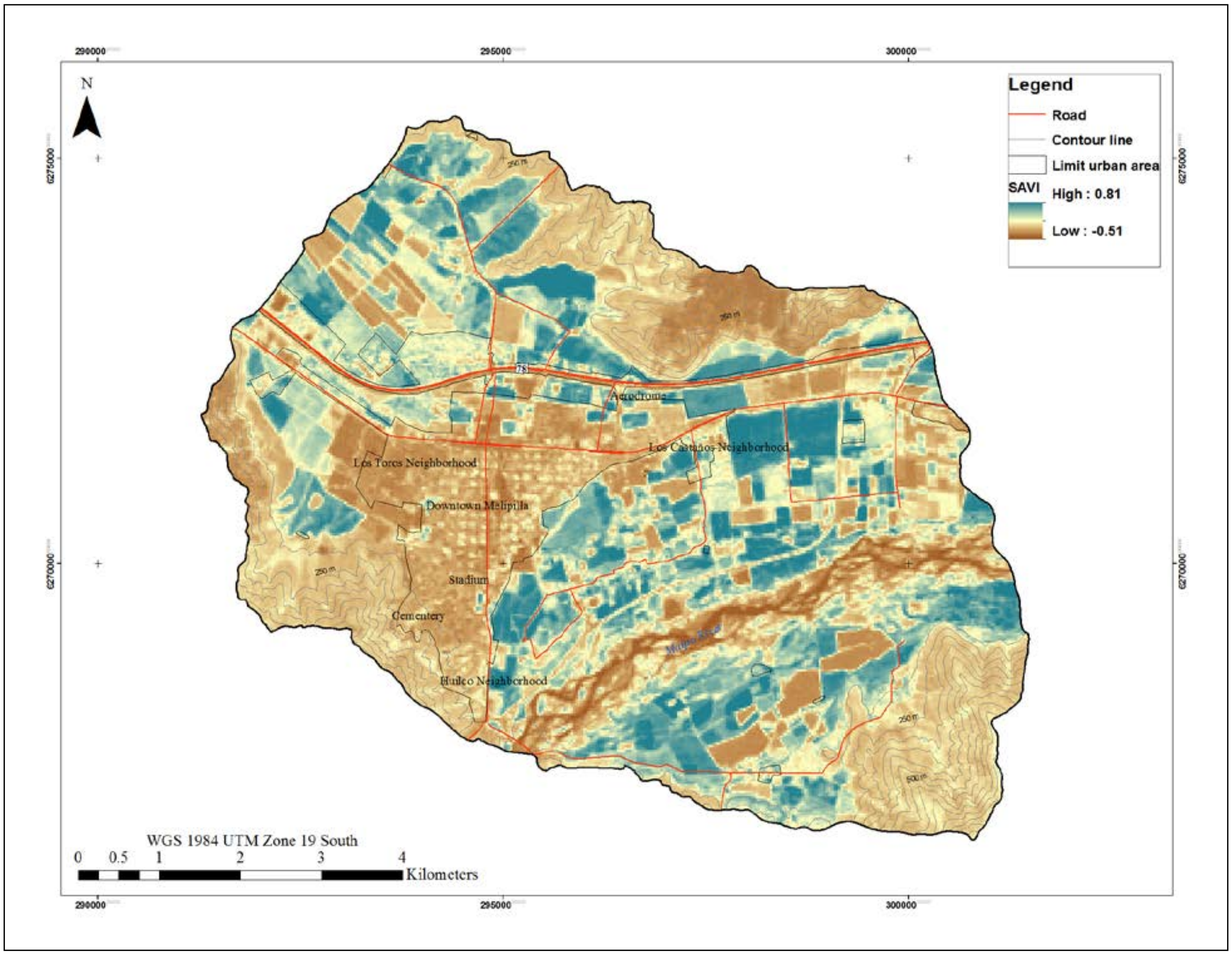


**Figure 17.** Map showing the SAVI values of the catchment surrounding Melipilla City

Reclassifying the SAVI values for both study areas, based on the vegetation density classes of Mark *et al.* (2001), it was possible to group sectors with similar vegetal coverage into five categories, from very low to very high coverage, which were associated with water erosion, from very slight to very severe current erosion, defined as Erosion Reference Units (ERefU).

In the basin surrounding Colina City, the distribution of current erosion depends not only on vegetation density, but also on the geomorphologic localization of biomass (Figures 18 and 19). Very severe erosion due to very low or no vegetal covering was identified mainly in the upper part of the Colina river valley, where the stream has eroded the base of river terraces by severe rotational landslides that create steep walls around some sections of the riverbed, and in the urban area of Colina where the terrain is degraded by human intervention, producing erosion in the form of gullies, with a surface coverage of 3% (Figures 20).

However, because of low vegetation coverage, about 63% of the catchment of the urban environment of Colina City is directly affected by severe erosion, including gullies and landslides. It should be noted that the zones with this category of erosion are situated along a north-south running system on the Chilean Coast Range and the Andes Mountain Range (Figure 21), which is covered by a sparse shrub surface. Furthermore, it was possible to identify severe present water erosion in the urban and sub-urban areas in contact with the agricultural area.

On the other hand, the areas which have the lowest categories of current water erosion are located not only in the contact zones between mountains and the bottom valley, but also on the alluvial terraces in the southern part of the basin surrounding Colina City. Moderate erosion by rill and gully erosion affects about 19% of the entire area and it is mainly in the natural landscapes outside the densely populated patches of urbanization, including farm land and some colluvial fans that are covered by scrubs vegetation. In relation to the slight and very slight ERefU categories, of rill and interrill erosion, these represent together about 15% of the 71.17 square kilometers, corresponding to cultivated areas with an extends vegetation coverage of crops and the rural residential areas of Chicureo and Las Brisas, which include urban parks.

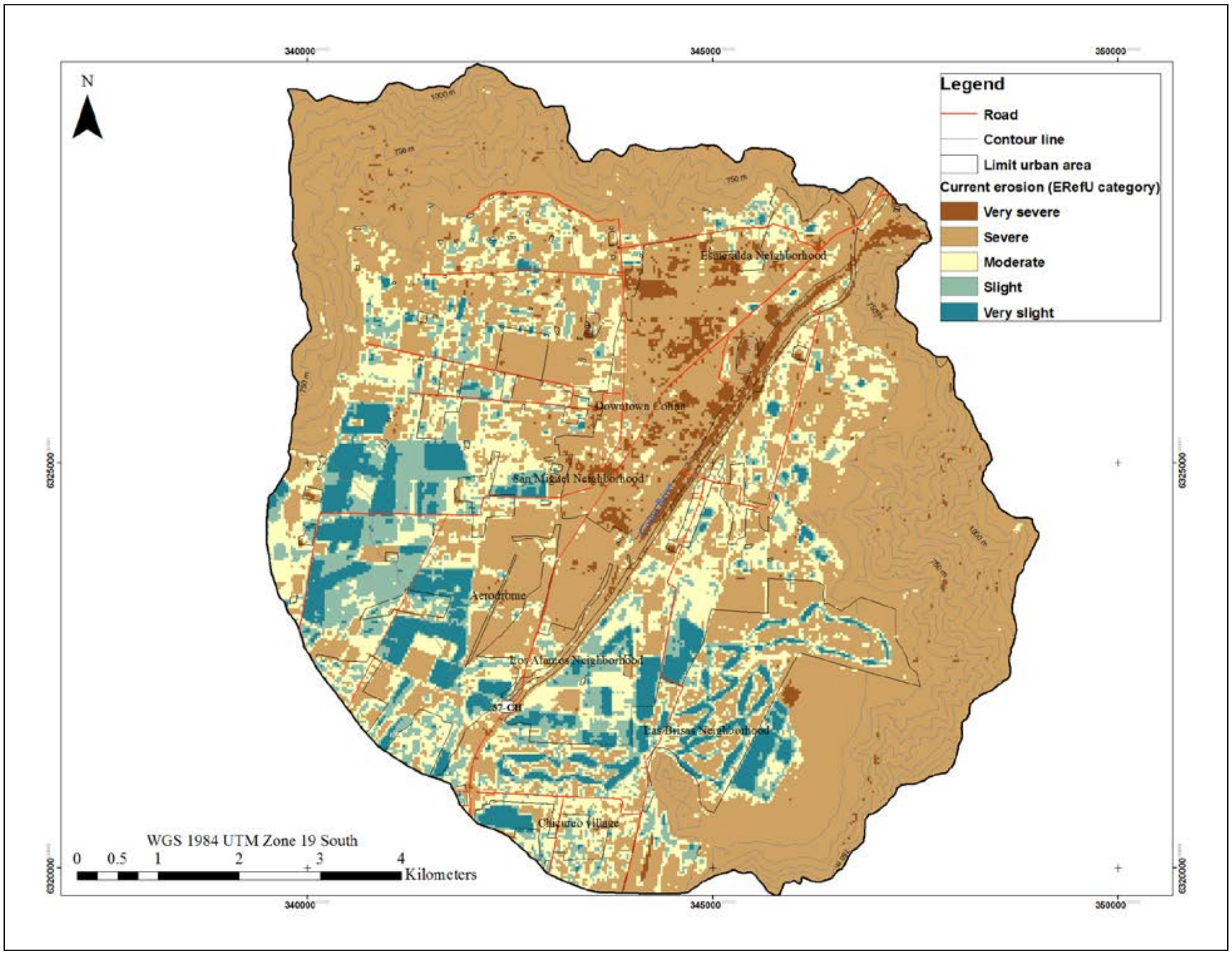


**Figure 18.** Map showing the current erosion of the catchment surrounding Colina City

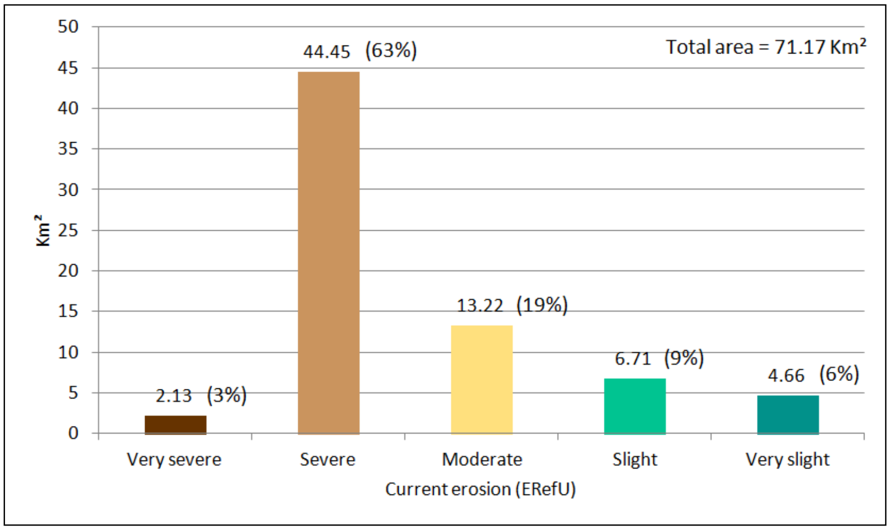


**Figure 19.** Graph showing the surfaces for current erosion categories of the catchment surrounding Colina City

**Figure 20.** View of a gully in the urban zone of Colina City (Roberto Fernández, 2011)

**Figure 21.** Picture showing landslides in the Chilean Coastal Range belonging to the study area of Colina City (Google Earth, 2011)

In the case of the basin surrounding Melipilla City, distribution of present water erosion processes depends on the geomorphological distribution of vegetation in the landscape (Figures 22 and 23). Only about 14% of the study area is affected by very severe erosion, associated with gullies and mass movements within the catchment due to a very low influence of vegetation; particularly in the wide Maipo, where rotational landslides produce steep walls, and in the densely populated urban area of Melipilla has contributed to the erosion the terrain for decades in the downtown and western neighborhoods.

A large portion of the study area, an area of 43%, displaces severe water erosion in the form of gullies and landslides in the mountains of the Chilean Coast Range (Figures 24), which are covered by a spare distribution of shrubs and bushes. In addition, this category was also identified in areas without agricultural terraces or dense vegetation and in the areas belonging to new urbanizations, from downtown Melipilla to the eastern neighborhoods of Los Castaños.

The areas with the lowest categories of current water erosion are mainly located in the piedmont of the mountains and the valley bottom on the fluvial terraces of the Maipo River surrounding Melipilla City. Moderate erosion by rill and gully affects about 22% of the 59.94 square kilometers in the natural landscapes and farmlands, which is covered by low and very low biomass (Figures 25). Outside the urbanized are of Melipilla, mainly in the northwestern part of the study area, where slight and very slight current erosion, about 21%, is associated with agricultural terraces around the Maipo River, flanked by the Chilean Coast Range in the north and the south of the basin.

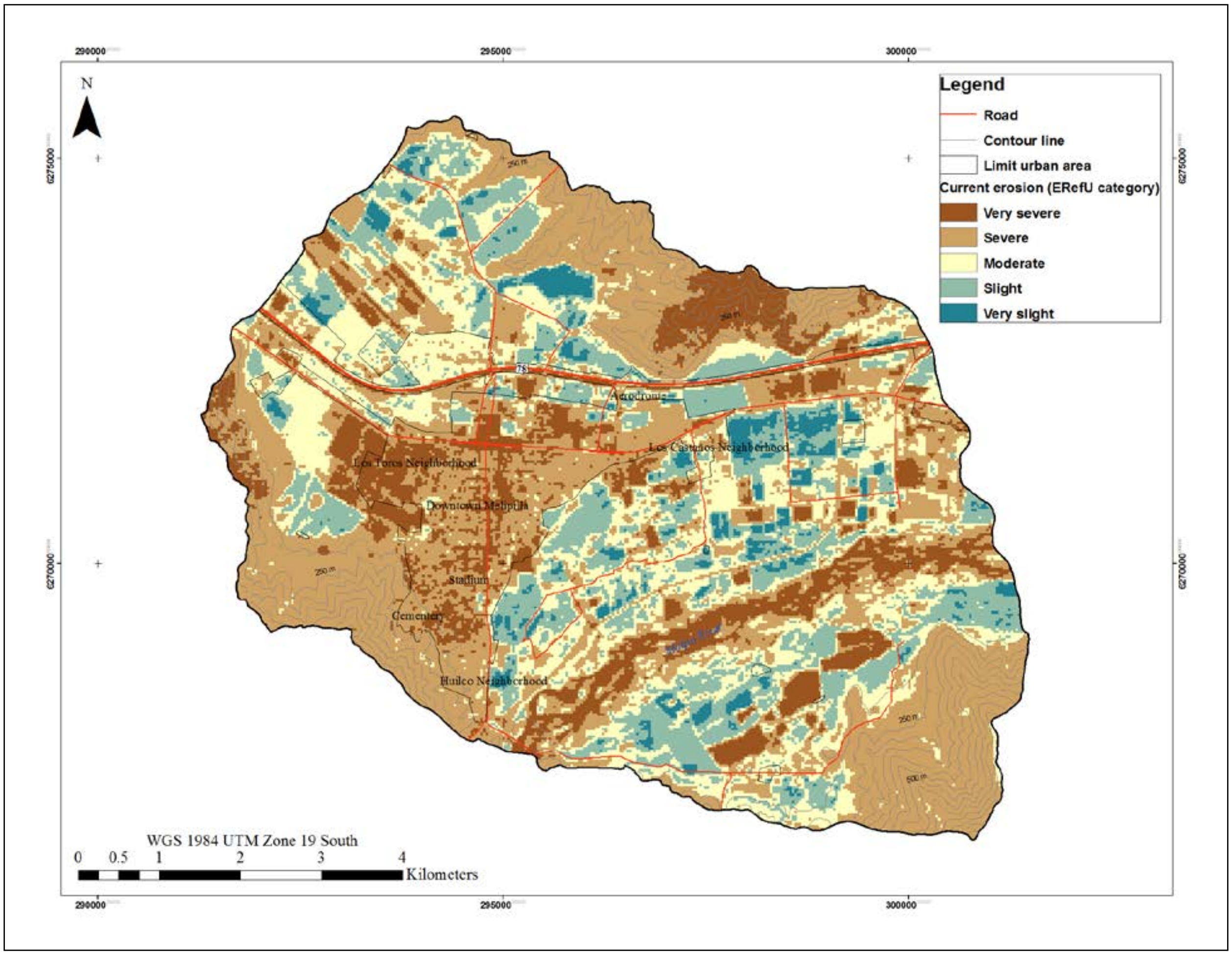


**Figure 22.** Map showing the current erosion of the catchment surrounding Melipilla City

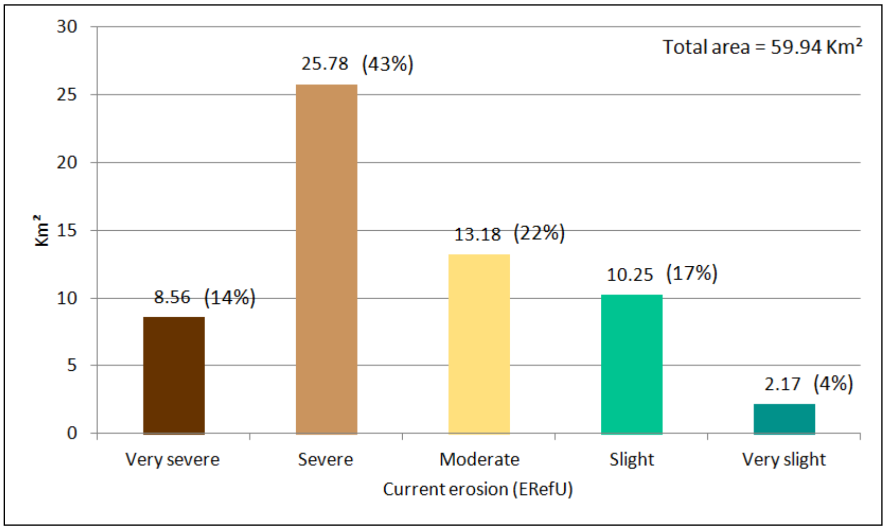


**Figure 23.** Graph showing the surfaces for current erosion categories of the catchment surrounding Melipilla City

**Figure 24.** Picture showing landslides in the Chilean Coastal Range belonging to the study area of Melipilla City (Roberto Fernández, 2011)

**Figure 25.** Panoramic view of rill erosion in the bottom valley belonging to the study area of Melipilla City (Municipality of Melipilla, 2011)

## Description of the Geographical Parameters

Based on the analysis of four geographical parameters, Stream Power Index (SPI), land use, soil texture, and lithology, in the urban environments of the city of Colina, it was possible to identify the main characteristics that configure the frame for the erosion processes (Figure 26 and Table 10). According to the morphology, about 85 % of this area of study presents the strongest SPI values, above 1,000, and about 15 % of the territory has the lowest SPI values, below 1,000. Observing these morphometric properties and their spatial distribution, it is clear that runoff tends to concentrate in intermountain streams in the Chilean Coast Range and the Andes Mountain Range, where it develops a stronger erosion capacity than the flatter areas.

In relation to the current land use, most of the basin of the city of Colina, with a surface of 63%, is used by a variety of human activities, such as industrial areas, transport ways, residential areas, or farmland (Figure 27). The remaining 37% of the area is cover by natural landscapes. The farmlands in the bottom of the valley dominate the area surrounding urbanized areas, with a total extent of 38% and 22% respectively, which are flanked by the mountains ranges that are covered by a surface of bushland and prairies, about 35% (Figure 28).

The urban environment of Colina City shows an abundance of clay texture, with an area of 44%; often over extrusive igneous rocks which belong to the Chilean Coast Range, and the Andes Mountain Range, which represent the consolidated material of this study area with about 24%. The alluvial sediments which are located on the bottom of the valley of the Colina River, with a surface of 66%, mainly covered by a superficial soil texture of loam and clay loam that covering an area of 52%.

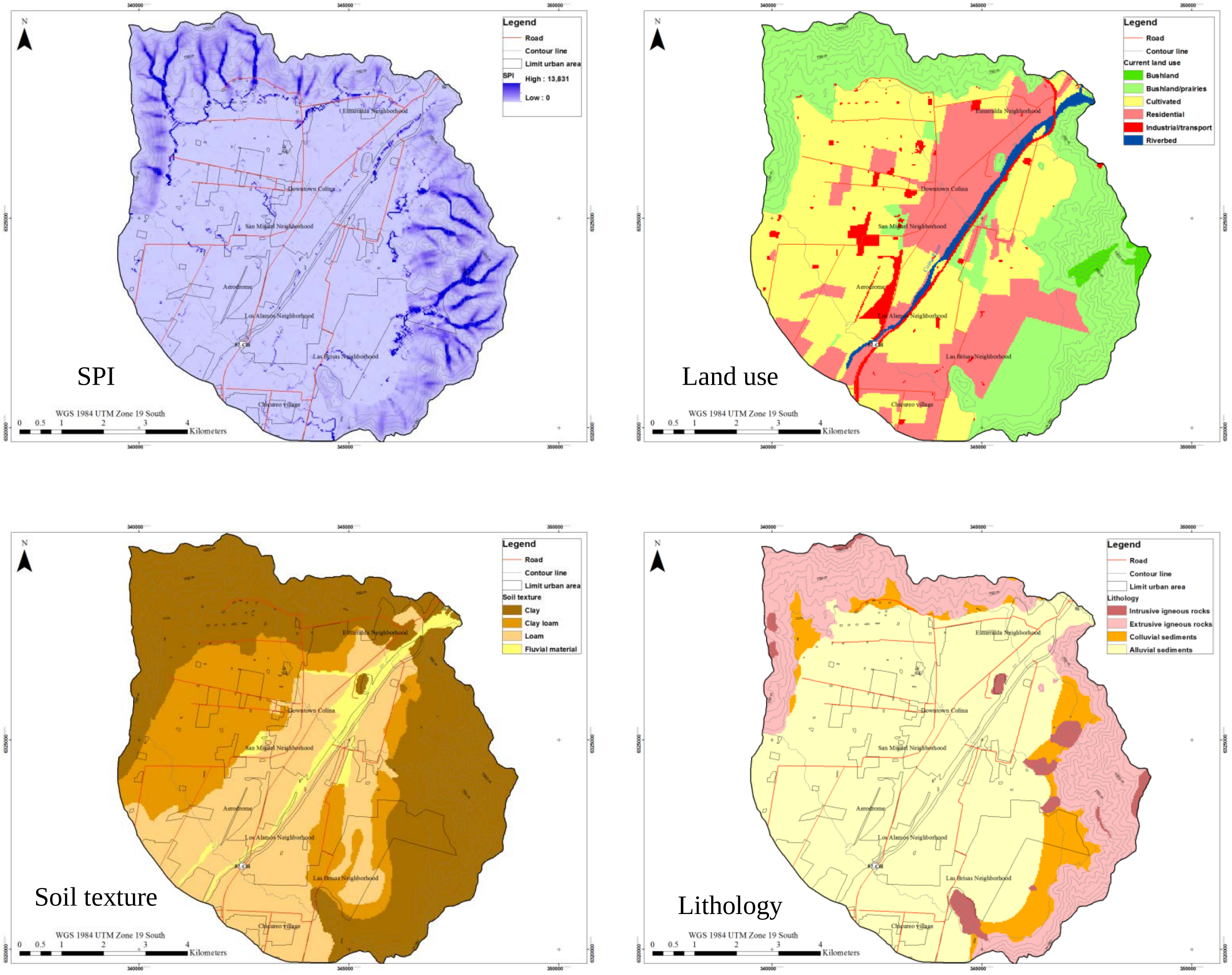


**Figure 26.** Maps showing the geographical parameters of the catchment surrounding Colina City

**Figure 27.** Picture showing the urban area of Colina City (Roberto Fernández, 2011)

**Figure 28.** Panoramic view of farmland in the study area of Colina City (Google Earth, 2011)

Based on the assessment of the same four geographical parameters, Stream Power Index (SPI), land use, soil texture, and lithology, in the urban environments of the city of Melipilla, the features that set the frame for the water erosion processes were identified for the entire study area (Figure 29 and Table 10). According to the morphology, about 89 % of this study area shows the strongest SPI values, above 1,000, and about 11 % of the area has SPI values, below 1,000. Thus, examining the topographic characteristics and their spatial distribution in the area, it is evident that runoff tends to concentrate in intermountain streams localized in the Chilean Coast Range, where it develops a stronger erosion capacity compared to the valley bottom due to the relationship between flow accumulation and slope.

The current land utilization, 33 %, of the study area belongs to natural areas of mainly bushland. However, most of the catchment of Melipilla City, a surface of 67 %, is occupied by human activities, such as farmland, industrial areas, transport, or urban areas (Figure 30). The farmlands, mainly vineyards and orchard, located in the bottom of the valley dominate the area surrounding urban areas, with a surface of 51 % and 14 % respectively, which are flanked by the Chilean Coast Range that are mainly covered by a densely bushland, about 14 % (Figure 31).

The catchment of Melipilla City presents a large extent of clay loam, about 36 %; over intrusive and extrusive igneous rocks belonging to the Chilean Coast Range, which correspond to the consolidated material of this urban environment with a surface of 28 %. The unconsolidated alluvial sediments which are located in the terraces of the Maipo River, with a total area of 65 %, which is mainly covered by soils of loam and sandy loam texture that cover a total surface of 54 %.

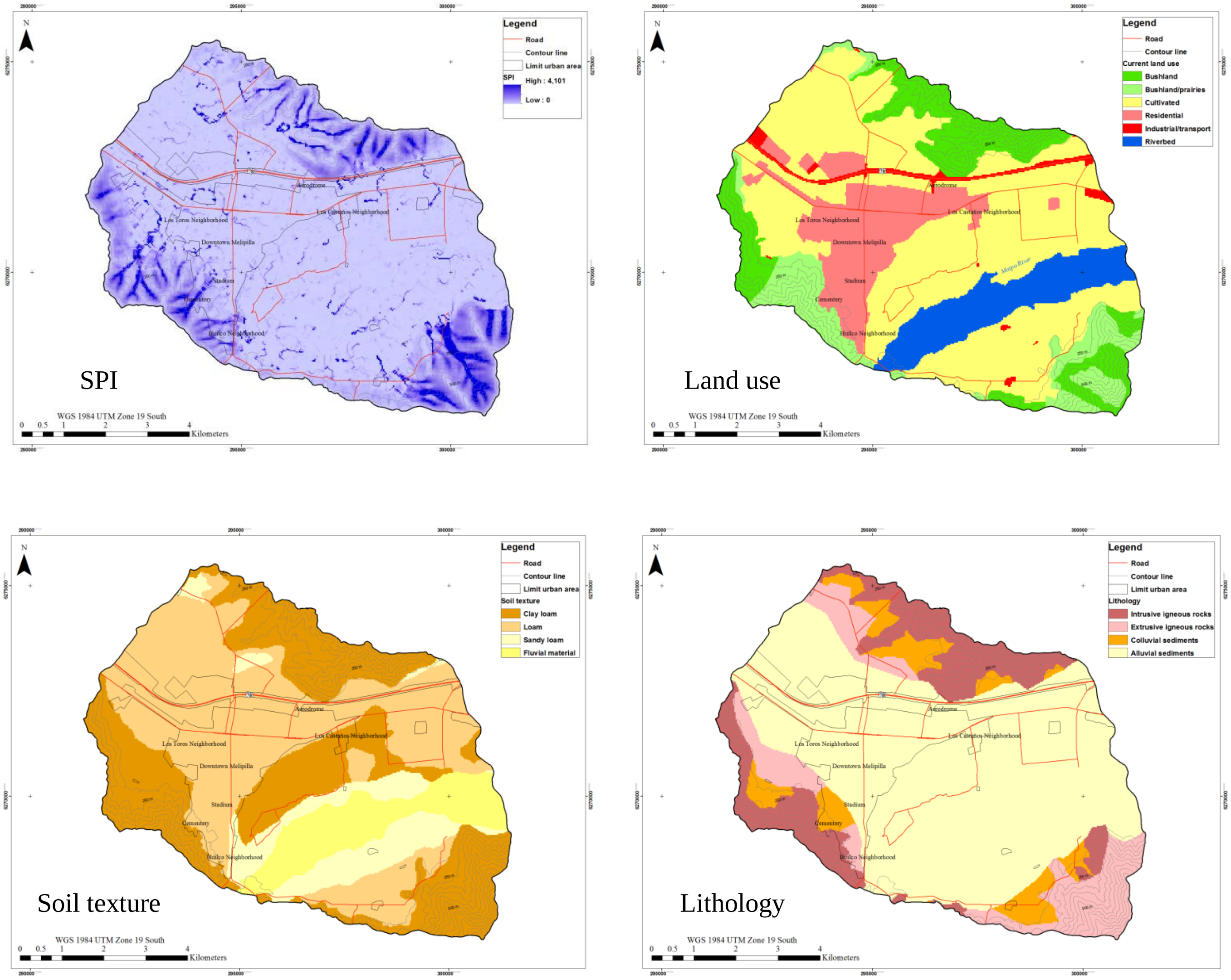


**Figure 29.** Maps showing the geographical parameters of the catchment surrounding Melipilla City

**Figure 30.** Picture showing the Central Square in the urban area of Melipilla City (Municipality of Melipilla, 2011)

**Figure 31.** Panoramic view of farmland surrounding the urban areas of Melipilla City (Google Earth, 2011)

Table 10. Spatial coverage of the mapped geographical parameters and their categories

| | Colina City | | Melipilla City | |
|---|---|---|---|---|
| Parameter | Area (Km²) | *Area (%)* | Area (Km²) | *Area (%)* |
| Topography (SPI) | | | | |
| Very high slope and flow accumulation | 0.18 | *0.26* | 0.03 | *0.05* |
| High slope and flow accumulation | 0.53 | *0.76* | 0.14 | *0.24* |
| Moderate slope and flow accumulation | 9.61 | *13.5* | 6.43 | *10.72* |
| Low slope and flow accumulation | 22.18 | *31.14* | 17.4 | *29.03* |
| Very low slope and flow accumulation | 38.67 | *54.34* | 35.94 | *59.96* |
| Land use | | | | |
| Riverbed | 1.11 | *1.56* | 5.85 | *9.76* |
| Industrial/transport | 2.02 | *2.84* | 1.32 | *2.2* |
| Residential | 15.56 | *21.86* | 8.27 | *13.8* |
| Cultivated | 27.19 | *38.2* | 30.74 | *51.29* |
| Bushland/prairies | 24.56 | *34.51* | 5.60 | *9.34* |
| Bushland | 0.73 | *1.03* | 8.16 | *13.61* |
| Soil texture | | | | |
| Fluvial material | 2.72 | *3.82* | 6.20 | *10.34* |
| Sandy loam | 0.00 | *0.00* | 6.64 | *11.08* |
| Loam | 21.71 | *30.5* | 25.5 | *42.54* |
| Clay loam | 15.17 | *21.32* | 21.6 | *36.04* |
| Clay | 31.57 | *44.36* | 0.00 | *0.00* |
| Lithology | | | | |
| Alluvial sediments | 47.12 | *66.21* | 38.67 | *64.51* |
| Colluvial sediments | 5.20 | *7.3* | 4.50 | *7.51* |
| Extrusive igneous rocks | 17.00 | *23.89* | 7.70 | *12.84* |
| Intrusive igneous rocks | 1.85 | *2.6* | 9.07 | *15.14* |

**Source:** Elaborated by author

## Estimation of Terrain Erodibility

Based on the evaluation of the erodibility data in the basin surrounding Colina City, obtained through the reclassification of its geographical parameters, it was possible to identify not only some patterns of distribution, but also correlation among the four types of erodibility (Figure 32 and Table 11). It is evident that the highest topographic erodibility categories are associated with the mountainous areas. The lowest categories are present in the valley between the Chilean Coast Range and the Andes Mountain Range. This spatial distribution is opposite the patterns of the other types of controls of erosion because the topographic erodibility shows a weak and moderate correlation with them.

The strong and very strong categories of land use erodibility occurs on the flatter area at the bottom of the valley, associated with urbanization, such as the consolidated urban zones of Colina City and the rural residential areas in the southeastern sector. In addition, it was possible to identify moderate erodibility of land use in flatter sectors and the mountainous ranges, farmland and sparse bushland respectively. Because this pattern of distribution is associated with some of the other types of controls of erodibility, it has a moderate correlation with the soil texture and lithology, 0.46 and 0.35 respectively.

In the catchment of Colina City the lowest categories of soil texture and lithological erodibilities are in the two mountain ranges and contact areas between the mountains and bottom valley, associated with clay and clay loam soils over extrusive igneous rocks. Conversely, the strongest erodibility categories are in the unconsolidated sediments located in the terraces which of the Colina River. For this reason, these two erodibilities have a strong correlation to each other, which is 6.1.

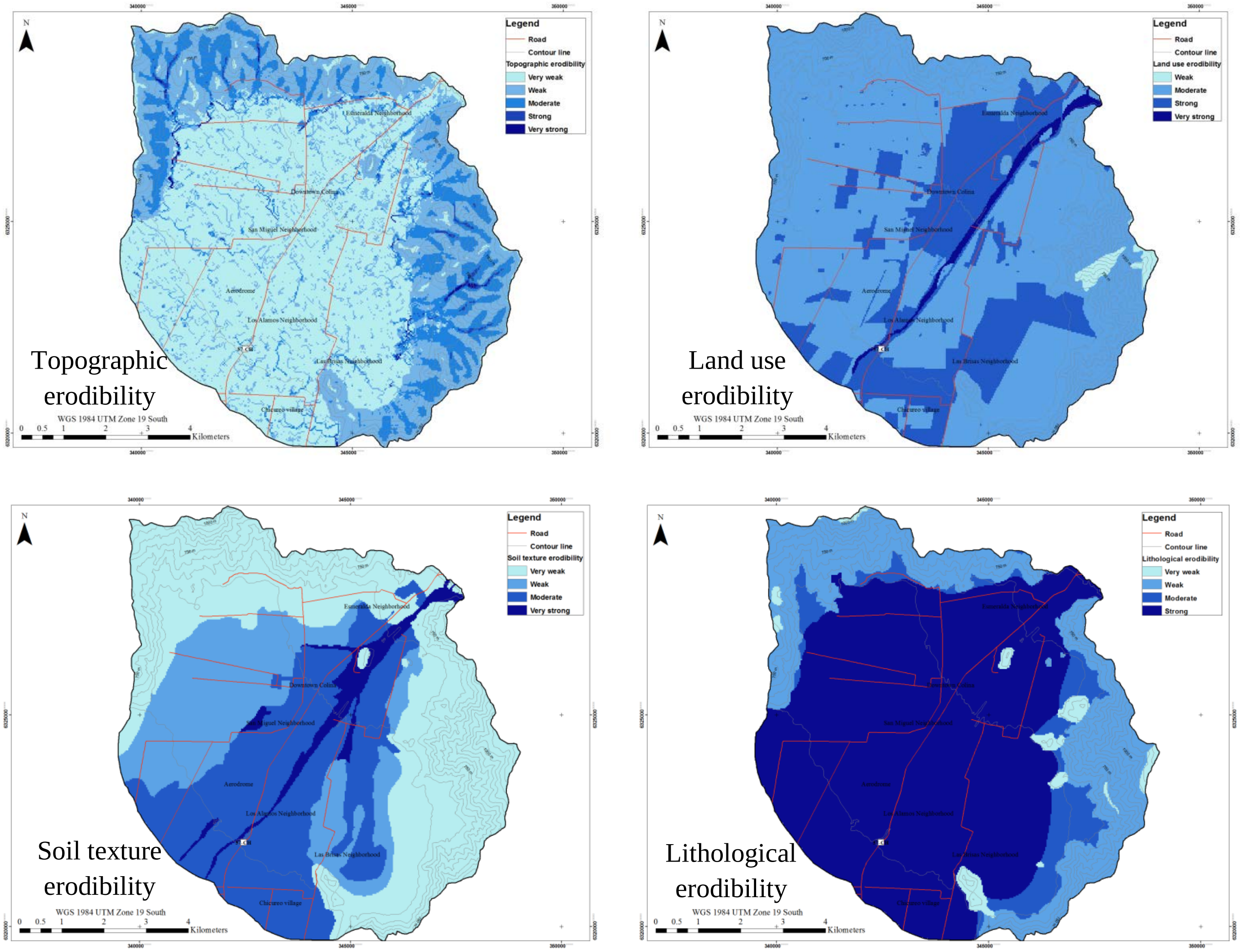


**Figure 32.** Maps showing the terrain erodibility of the catchment surrounding Colina City

In the case of Melipilla City, the assessment of erodibility patterns of distribution and correlation among the four types of terrain erodibility was similar to the situation of Colina City (Figure 33 and Table 11). Thus, the highest levels of topographic erodibility are located on the slopes and streams belonging to the mountainous systems of the Chilean Coast Range, and the lowest categories of topographic erodibility are in the bottom of the valley. Nevertheless, due to the fact that this pattern is different than the other patterns of erodibility, the topographic erodibility in the environment of Melipilla City shows a moderate correlation with them.

In relation to the land use erodibility, the strong and very strong categories are located on the flatter area at the bottom of the valley, associated with the consolidated urban area of Melipilla City and the wide riverbed of the Maipo River that crosses the catchment from east to west. However, the moderate erodibility mainly corresponds to agricultural land, over terraces surrounding the riverbed, and the weak erodibility associated with areas covered by a dense bushland on the slopes and stream of the mountains. Consequently, it particularly presents a strong correlation with the soil texture and lithological erodibilities, 0.66 and 0.53 respectively.

The urban environment of Melipilla shows that the lowest categories of soil texture and lithological erodibilities are in the Chilean Coast Range and contact sectors between the mountains and bottom valley. On the other hand, the strongest erodibility categories of these two parameters are in the sediments of the bottom valley. These two erodibilities have a moderate-strong correlation of 5.4.

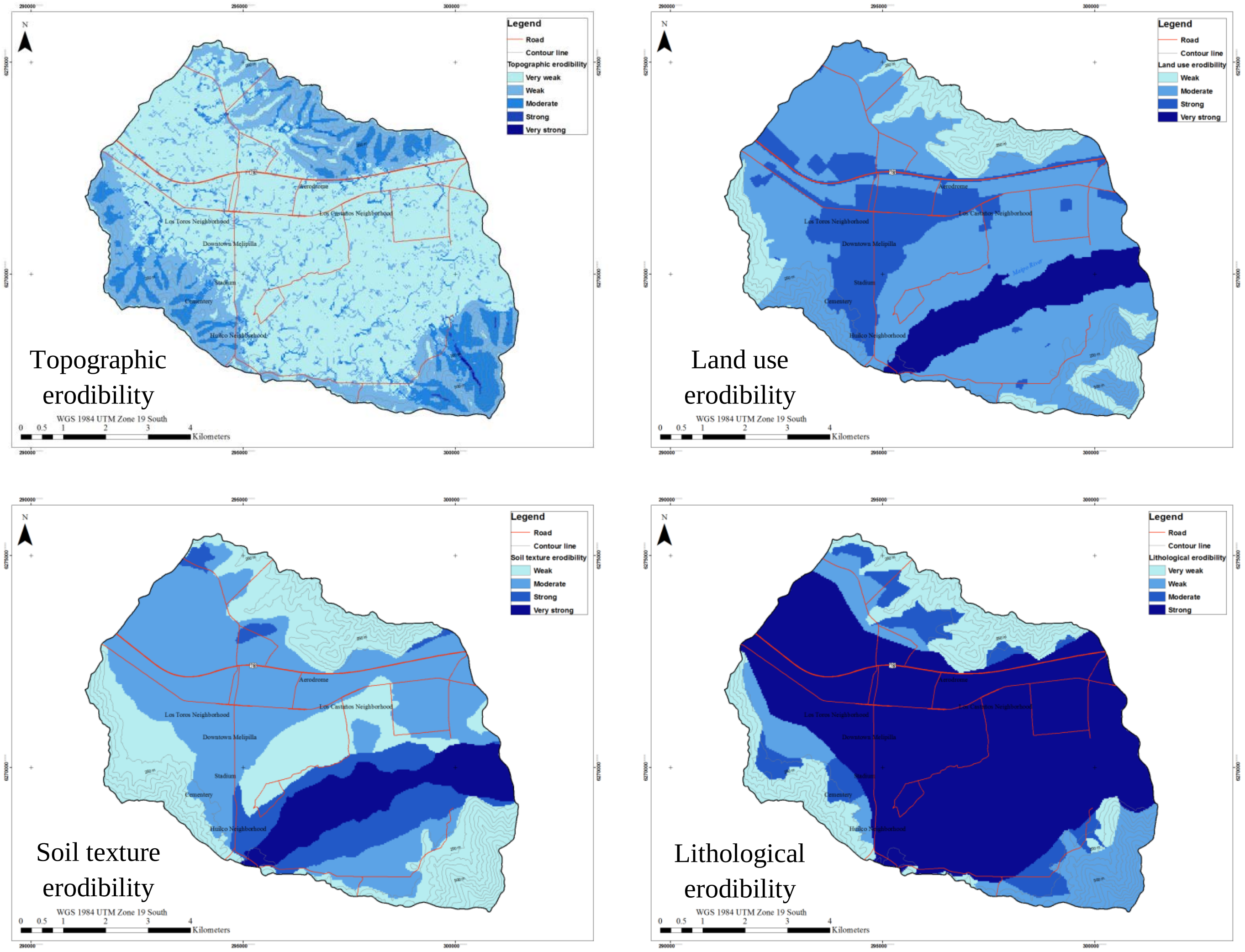


**Figure 33.** Maps showing the terrain erodibility of the catchment surrounding Melipilla City

Table 11. Matrix of Pearson's correlation coefficient between erodibility types

| Colina City | | | | |
|---|---|---|---|---|
| | Topographic erodibility | Land use erodibility | Soil texture erodibility | Lithological erodibility |
| Topographic erodibility | 1.00 | -0.25 | -0.51 | -0.59 |
| Land use erodibility | -0.25 | 1.00 | 0.46 | 0.38 |
| Soil texture erodibility | -0.51 | 0.46 | 1.00 | 0.61 |
| Lithological erodibility | -0.59 | 0.38 | 0.61 | 1.00 |
| Melipilla City | | | | |
| | Topographic erodibility | Land use erodibility | Soil texture erodibility | Lithological erodibility |
| Topographic erodibility | 1.00 | -0.36 | -0.40 | -0.58 |
| Land use erodibility | -0.36 | 1.00 | 0.66 | 0.53 |
| Soil texture erodibility | -0.40 | 0.66 | 1.00 | 0.54 |
| Lithological erodibility | -0.58 | 0.53 | 0.54 | 1.00 |

**Source:** Elaborated by author

### Definition of the Erosion Response Units (ERU)

The hierarchical model of the parameters and erodibility categories considered in the evaluation of the erosion susceptibility in the urban environments of the cities of Colina and Melipilla, using a multicriteria processing, shows the weights in relation to their importance to the stated objective (Figure 34 and appendices tables 1-6). Because of the evident influence of the ERefU on the erosion susceptibility of the terrain, it was assigned with the greatest weight in the hierarchy, about 46 %. However, the topographic features are essential for water erosion processes compared to other geographic characteristics; consequently, it is around 25% of the total importance in the hierarchical model. Finally, because the land use, soil texture, and lithological erodibilities have a moderate spatial correlation among each other, and they have lower influence than the current erosion and topographic erodibility, these parameters were assigned with the same weight, which is about 10 % each one.

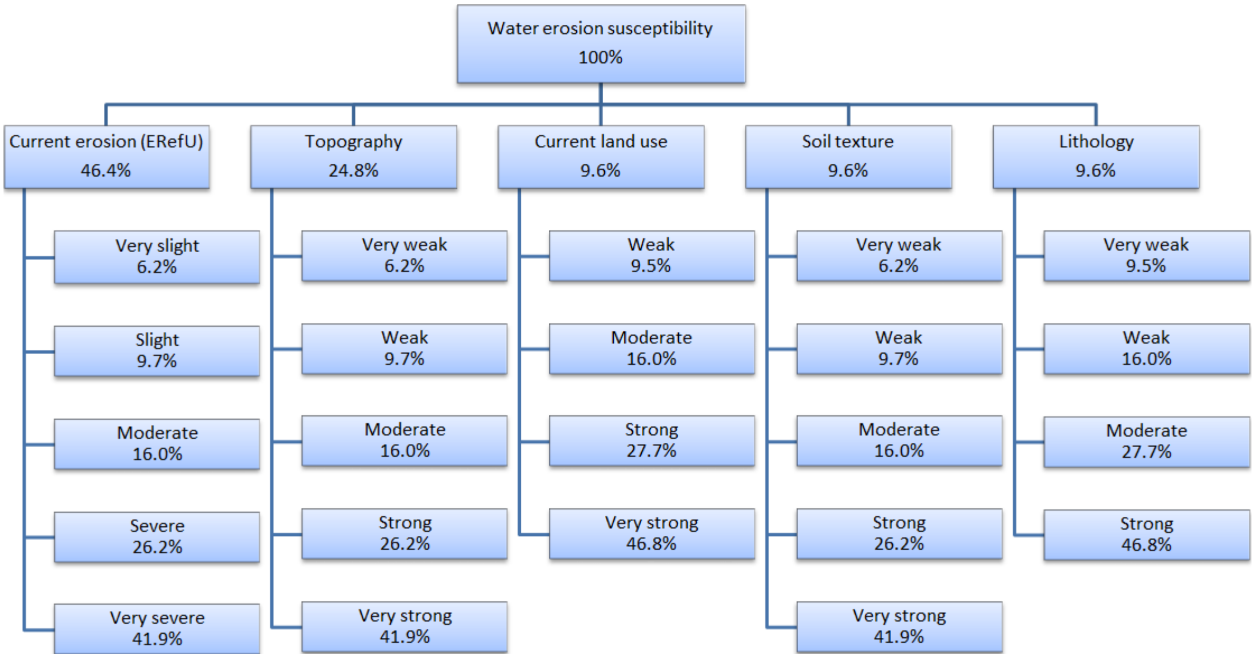


**Figure 34.** Graph showing the objective pursued, water erosion susceptibility, as well as the parameters considered, using a hierarchical model

The Consistency Ratio (CR) calculated for this hierarchical model was 0.023. Therefore, the model and the weight of the each element have a logical structure, which it is acceptable with respect to the stated objective of this thesis because the CR does not exceed the value 0.1. In other words, the judgments have been relative consistent to problem statement of the project.

After this weighting, it was possible to define the ERU by a map overlay of the weighted parameters for the areas of Colina City, where the ERU values are from 0.068 to 0.428, with a mean and standard deviation of 0.311 and 0.087 respectively (Figure 35). By performing a spatial analysis of these ERU in the terrain, it is clear that the largest ERU values are not only located in the urbanized area of the city of Colina, but also in the mountains systems that flank the valley bottom. Conversely, the lowest ERU values are placed in the bottom valley associated with flatter areas of the catchment belonging to the Colina River.

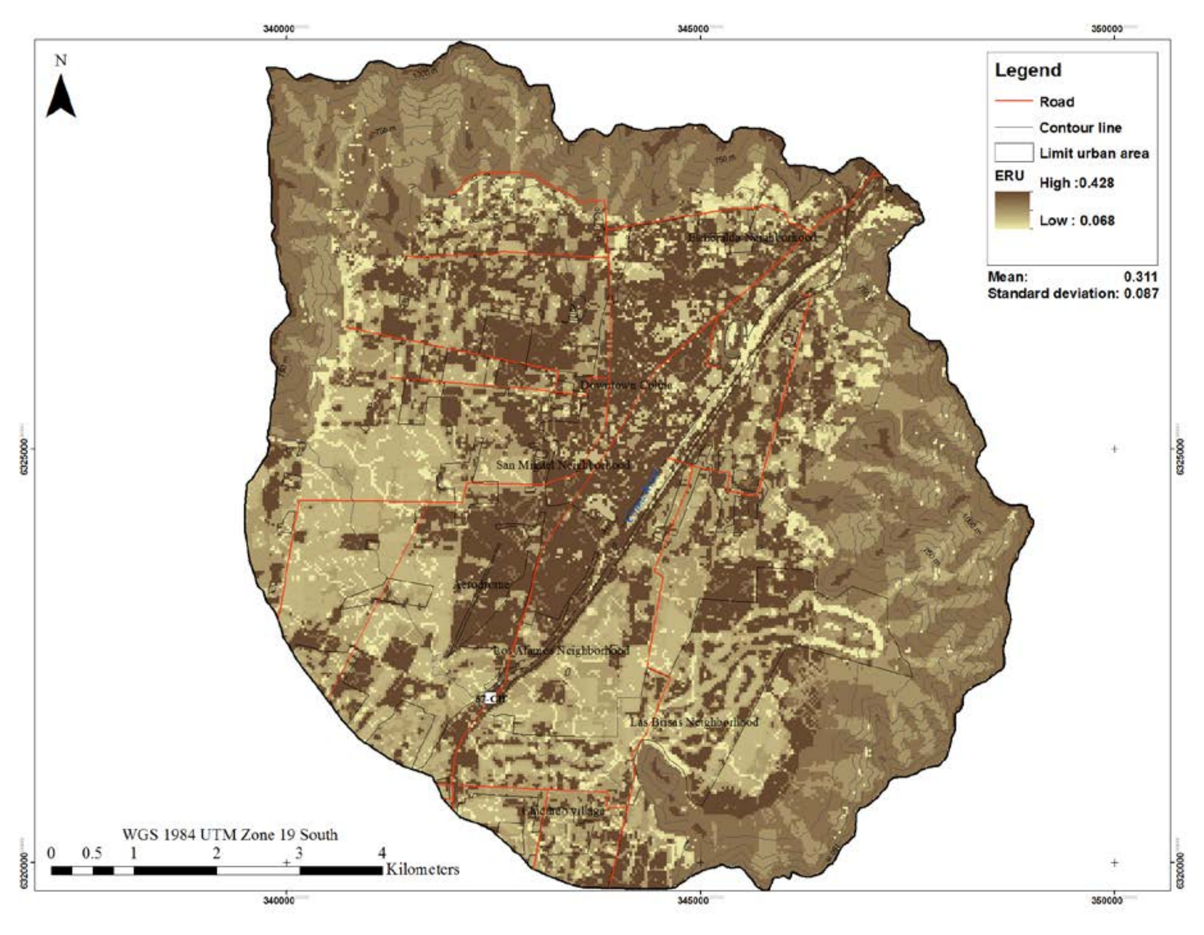


**Figure 35.** Map showing the ERU of the catchment surrounding Colina City

Using the same map overlay process, it was possible to determine the ERU of the weighted parameters and their categories of erodibility for the Melipilla City urban environment, where the ERU values are from 0.072 to 0.428, with a mean and standard deviation of 0.307 and 0.081 respectively (Figure 36). In a brief evaluation of these ERU in the terrain, it is evident that the largest ERU numbers are not only in the urbanizations belonging to Melipilla City and the Maipo riverbed, but also in some mountainous system. On the other hand, the lowest ERU values are mainly located in the mountain range which flanks the bottom valley.

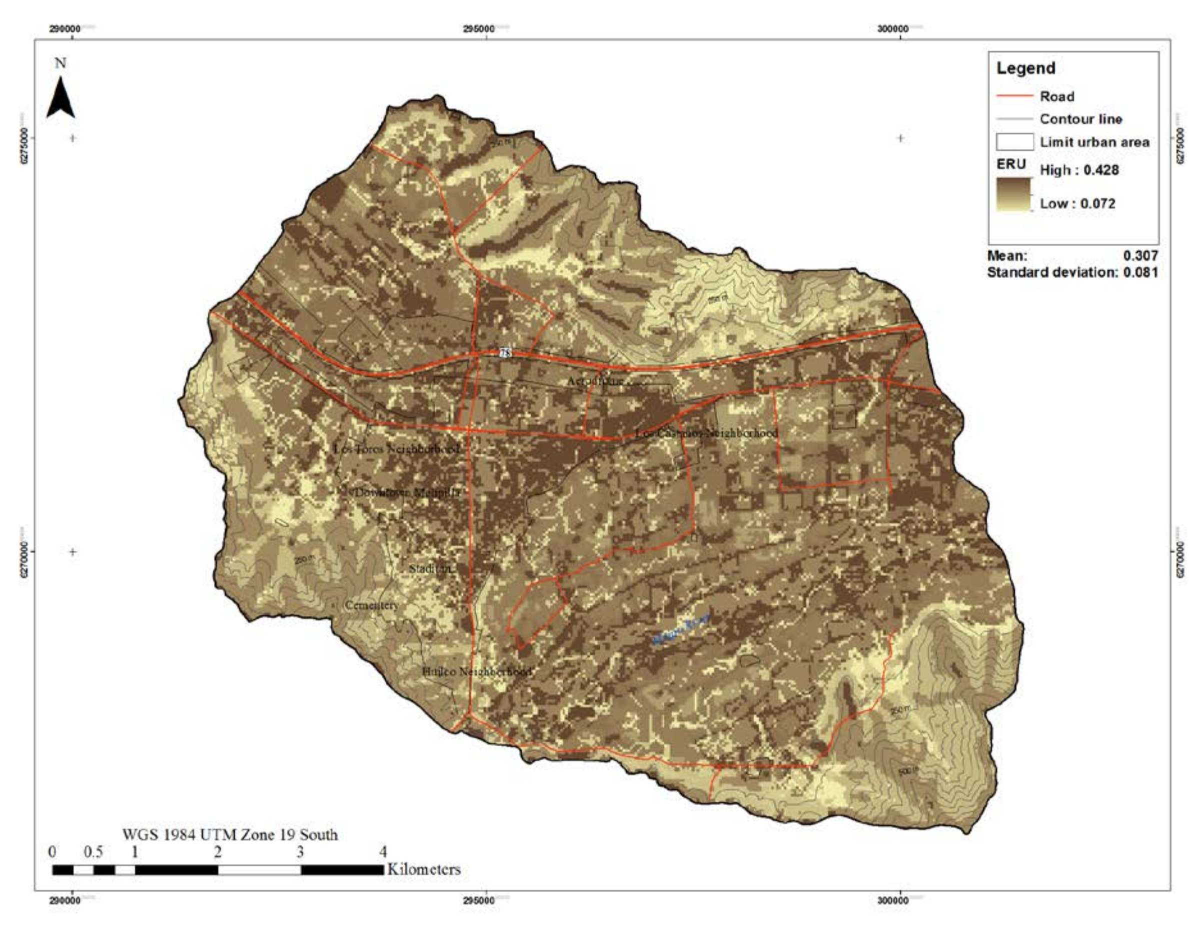


Figure 36. Map showing the ERU of the catchment surrounding Melipilla City

## Water Erosion Susceptibility and Land Use Suitability

By reclassifying ERU values obtained for the basins belonging to the urban environments of the medium-sized cities of Colina and Melipilla, this research project not only determines the susceptibility of water erosion processes, but also categories of land use suitability of the terrain.

Colina City, the very strong water erosion susceptibility is in the valley bounded by mountains belonging to the Chilean Coast Range and the Andes Mountain Range, with about 25 % of the 71.17 square kilometers. It is related to the consolidated urban zone of Colina City and the rural residential properties, over partly consolidated sediments, which present very severe or severe current erosion produced by gullying. As a result of all these characteristics, the areas within this category of susceptibility do not have suitability to support non-urban land uses (Figures 37 and 38).

On the other hand, the spatial distribution of the strong and moderate categories of water erosion susceptibility, 36 % and 34 % respectively, shows an increasing trend from the bottom of the valley to high altitude. Along the same lines, the strong category is situated along a north-south running system on the Chilean Coast Range and the Andes Mountain Range covered by sparse bushland, which have severe erosion associated with gullies and landslides on moderate and steep slopes. Thus, even though the mountains are natural environments, they present marginal suitability because they have limitations so severe that benefits are reduced for other land uses. The moderate category is completely situated in the bottom valley on the farmland and the suburban sectors surrounding the urban areas, over partly consolidated soil and alluvial sediments from the Colina River. Therefore, these lands are clearly suitable for several uses, but they have limitations.

Landscapes with weak and very weak categories of erosion susceptibility just represent about 5 % of the area, without a particular spatial distribution. Because of this condition, these areas are suitable and highly suitable for several types of land uses.

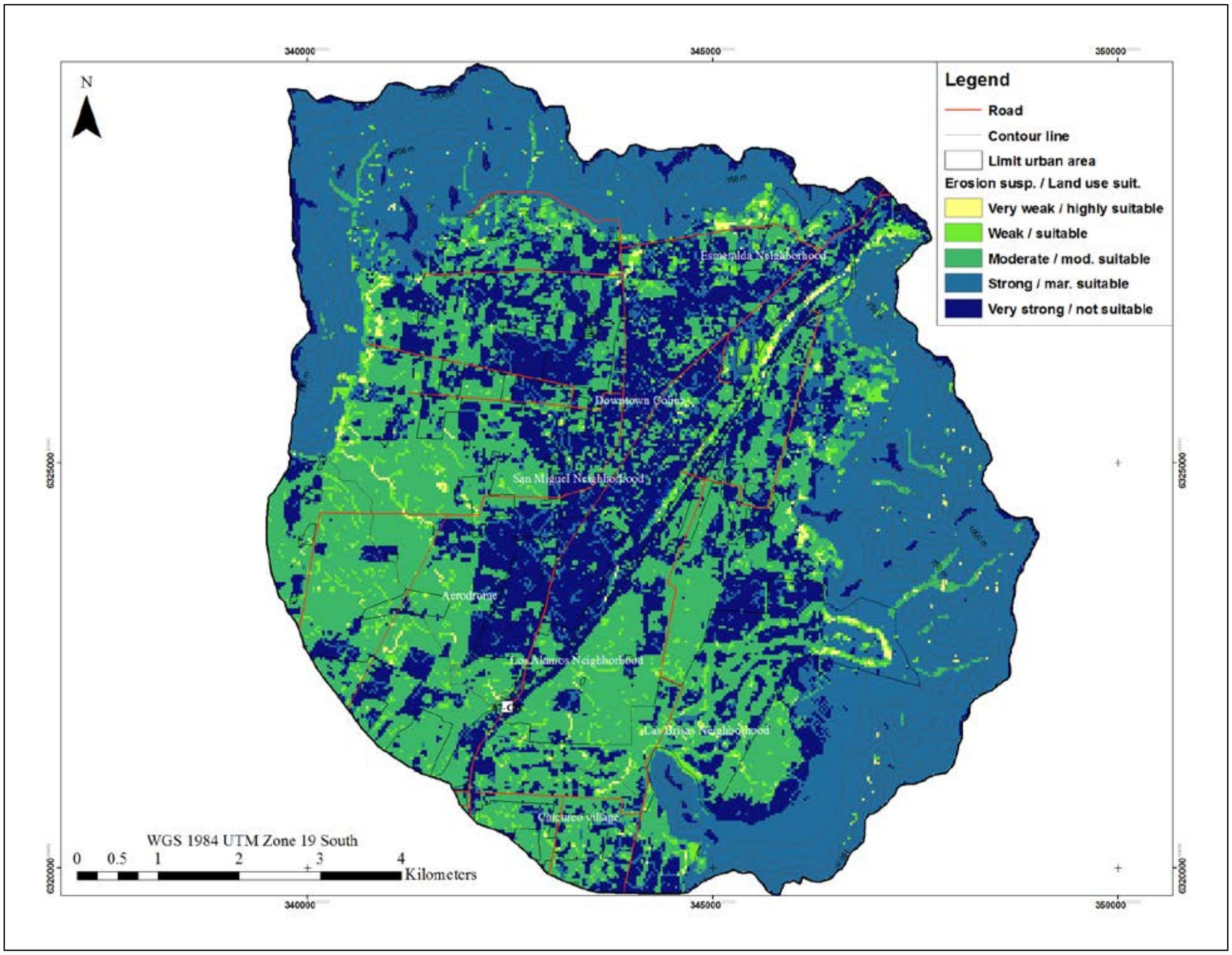


**Figure 37.** Water erosion processes' susceptibility and land use suitability of the catchment surrounding Colina City

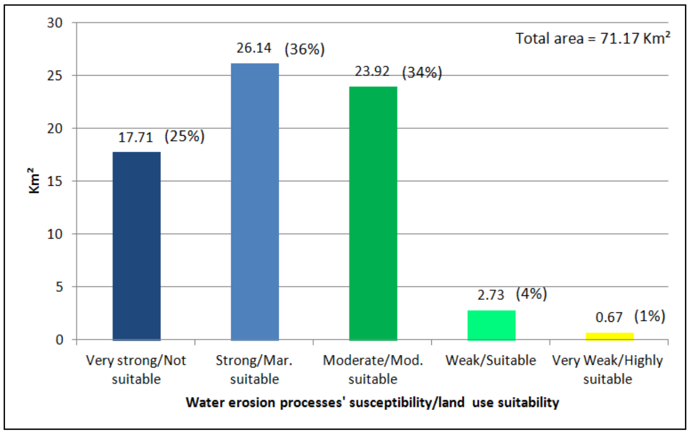


**Figure 38.** Graph showing the surfaces for water erosion processes' susceptibility and land use suitability of the catchment surrounding Colina City

In the basin of Melipilla City, the very strong water erosion susceptibility is located in the valley bounded by mountains belonging to the Chilean Coast Range, with about 19 % of the 59.94 square kilometers, and it is related not only to the consolidated urban zone of Melipilla City, but also the wide Maipo Riverbed, which presents very severe and severe current erosion associated with gullying and land sliding. For this reason, with all these features, the area within this category cannot support non-urban uses (Figures 39 and 40). In addition, the strong erosion susceptibility category, with a surface of 54 %, is located in the farmland patches of vineyards and orchard, over alluvial terraces surrounding the Maipo River that are covered by a unconsolidated soils of loam and sandy loam, with current erosion processes dominated by gullies. Therefore, these landscapes have marginal land use suitability because they present limitations so severe that the benefits are reduced for other utilizations.

The spatial distribution of the moderate category of erosion susceptibility in the terrain, about 19 %, shows that it is located on the intrusive and extrusive igneous rocks which belong to the Chilean Coast Range, with very weak and weak erodibility respectively. They are covered by bushland associated with severe current erosion by gullying in clay loam soils. As a result of these features, the areas within this category of susceptibility have moderate suitability to support several uses, but they have limitations.

The areas with weak and very weak categories of erosion susceptibility only represent about 8 % of the entire area of study, with a particular spatial distribution in the mountain systems that flank the bottom valley. Because of this situation, these lands are suitable and highly suitable for several types of uses.

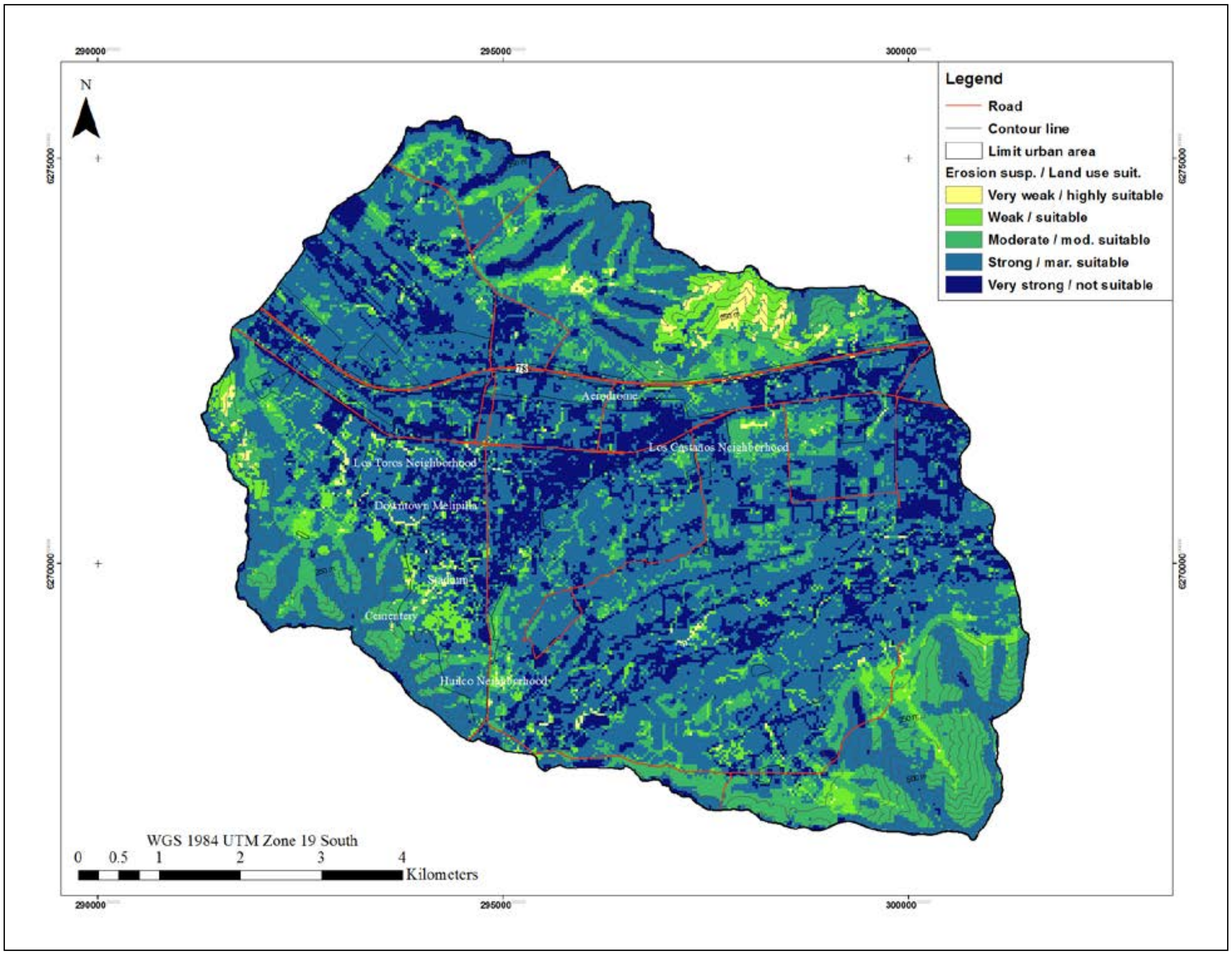


**Figure 39.** Map showing the water erosion processes' susceptibility and land use suitability of the catchment surrounding Melipilla City

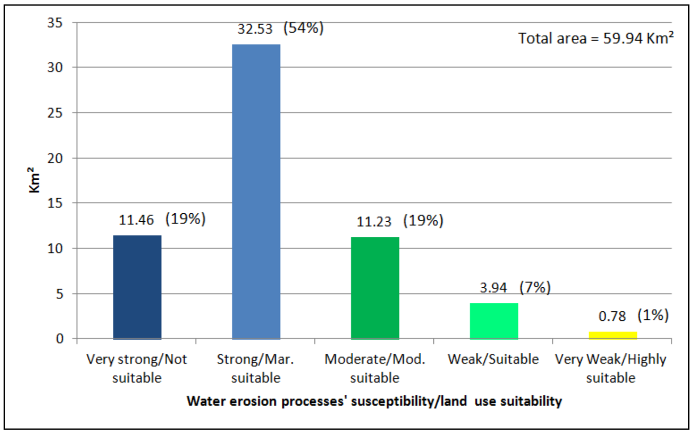


**Figure 40.** Graph showing the surfaces for water erosion processes' susceptibility and land use suitability of the catchment surrounding Melipilla City

## Quantitative Correlation Analysis

In order to sharpen the analysis from the final results in both areas of study, the current erosion was statistically correlated to water erosion susceptibility and land use suitability data, derived from the ERU. It was calculated using Pearson's R statistical correlation. In the catchment of Colina City, the positive linear relationship between these two variables was strong, with a value of *0.75*, because many points fall near a straight line for strong correlation on the scatter-plot (Figure 41). In the catchment of Melipilla City, the positive linear correlation between the existing erosion and erosion susceptibility/land use suitability was moderately-strong, with a value of *0.54*, due to the fact that the localization of the points in the scatter-plot diverges moderately from a straight line (Figure 42).

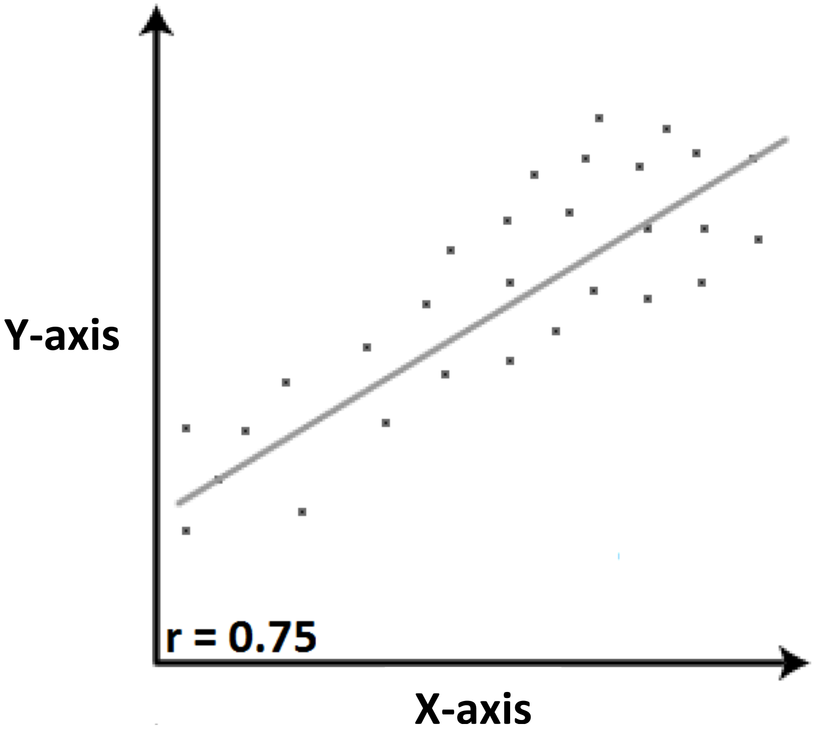


**Figure 41.** Correlation between current erosion and water erosion susceptibility/land use suitability in the study area of Colina city.

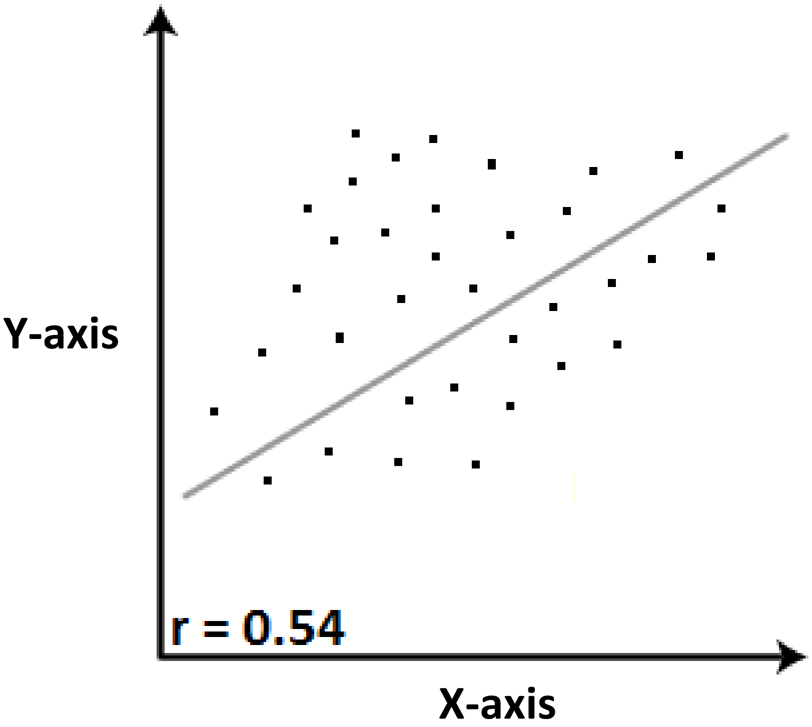


**Figure 42.** Correlation between current erosion and water erosion susceptibility/land use suitability in the study area of Melipilla city.

## VI. DISCUSSION

The data derived from the methodology and results presented in this study indicate that it is possible to assess and analyze the land use suitability of medium-sized urban areas based on water erosion susceptibility by embedding an integrated modelling framework. The following discussion details the results and is primarily an analysis of the parameters that compose the overall geographic characteristics of the terrain which not only determine landscape processes, such as erosion, but also the human interaction with the natural environment by farming and urbanization. Therefore, this methodological framework can be applied to other cities in other environments, but caution should be made with features such as urban area size because this methodology was used in medium-sized cities in Chile and in the case of longer urban areas this methodological approach probably requires adaptation.

By using the Analytical Hierarchy Process, AHP, defined by Saaty & Kearns (1991), and the weighted overlay technique, it was possible to analyze the problem statement of this research, which required the analysis of different parameters. This analysis allowed organization of the elements of the environment because which may not be equally important in erosion susceptibility and land use suitability for a particular activity. In other words, the weighted overlay approach allowed different weights to be applied to the thematic layers of geographic information (current erosion, topography, land use, soil, and lithology), which is shown in Figure 26. After processing, the output data is a raster grid file containing the Erosion Response Units (ERU), where each cell stores a number which indicates its level of importance in relation to water erosion, providing an accurate modelling structure for the areas of study.

The importance of the interaction between geographical factors for determining the erosive response of the terrain, from the point of view described by to Märker *et al.* (2001), was ratified in relation to the spatial distribution of the erosive susceptibility levels in the landscape of the urban environments of Colina and Melipilla, which reflects the principle of exchange of energy and matter between the elements of the environment, considered as a system that tends to equilibrium. Along the same lines, the homogeneous areas analysis of current and potential erosion dynamics, by incorporation of the concepts of Erosion Reference Units (ERefU) and Erosion Response Units (ERU), was essential for recognizing the role of these phenomena at different spatial scales, from interrill to landslides process. Once the ERU were identified, this information could be used in the erosion modelling.

The spatial distribution of the erosion susceptibility and land use suitability categories can be correlated with certain patterns. The results showed that vegetation cover and topographic patterns have greater influences on the current and future water erosion dynamics than other geographic parameters because, especially in the study area of the City of Colina, these delineate the localization of the erosion processes in the terrain, which is corroborated by authors such as Morgan (1995) and Vieira & Dabney (2011). Nevertheless, land use affects water erosion, particularly on farmland and in urban areas for both areas of study (Giovannini *et al.*, 2001 and Van Rompaey *et al.*, 2002).

Thus, in the basin surrounding the city of Colina, shown in Figure 37, lets the highest degrees of erosion susceptibility are associated with relief associated with mountain ranges and the lower levels that are located at the bottom of the valley on the alluvial sediments of the Colina River, which is due to the stabilizing condition of vegetation and topography. It was corroborated by the correlation analysis, Figure 41, which shows that the presence of biomass strongly controls the landslides and water erosion. However, for this scenario, it was possible to identify that spatial configuration of the land uses and the materials that support them, soil texture and lithology, produces an influence on some sector of the valley, particularly in the urban areas where all these characteristics configure a landscape with a high potential for water erosion processes. As a result, the highest categories of land use suitability associated with lowest degrees of erosion susceptibility are limited to agricultural fields surrounding the consolidated urban zone and the Colina River because in general these can support different land uses. In contrast, the sectors without the influence of agricultural terraces showed major impacts from water erosion at the catchment scale and the lowest degrees of land use suitability to support a different use from the current.

In the case of the urban environment of the Melipilla City, Figure 39 demonstrates that not only the location of current erosion and topography, but also the superficial soil texture and lithology within the landscape has an impact on the spatial distribution of erosion susceptibility categories in the study area, similar finding are reported by Morgan (1995) and Kuhni & Pfiffner (2001). It was corroborated by the correlation statistical analysis, Figure 42, which basically shows that biomass moderately correlates with water erosion. The strong categories of water erosion susceptibility are connected to the bottom valley, and some slope on the mountains belonging to the Chilean Coast Range, which showed the important function of the materials that compose especially the agricultural terraces surrounding the Maipo River. However, similar to the situation in the Colina City basin, the consolidated urban zones display the highest degrees of water erosion susceptibility because these areas represent a very strong impact on the natural environment by human buildings. Consequently, the sectors that showed lesser impacts from erosion and the major degrees of land use suitability are located on some slopes of the mountains, where soil and lithological material are much more consolidated than the valley.

## VII. CONCLUSIONS

This work has shown the importance of the evaluation of water erosion susceptibility and its relationship to land use/cover characteristics on the terrain, fundamentally in urban areas belonging to a Mediterranean climate environment. Water erosion has a significant capacity to modify the landscape and can influence the distribution of anthropogenic activities. Thus, it was possible to model the land use suitability of medium-sized cities and their surrounding environment based not only on the assessment of their geographic potentialities and weaknesses, but also on water erosion. For this reason, the application of different methodologies to analyze erosion in complex scenarios lets one recognize its potentialities and weaknesses regarding land use suitability. However, the model demonstrated in this study can be improved by adding new criteria specific to the problem.

This research proposed a hierarchical approach (AHP) to solving a layout design problem. It was observed that AHP can be used in the theme area of selection and evaluation of geographic parameters. These results showed that the parameters of water erosion susceptibility have different effects on land use suitability in the terrain. In the same way, it was observed that the relative importance of the parameters varies among urban areas, thus generating immediate effects on the suitability of landscapes in urban environments.

The applied methodology, based on GIS analysis of geographic data, made it possible to locate the areas where erosion exists as well as to obtain an estimation of potential erosion. The example of the Chilean test catchments shows that areas subject to different water erosion processes can be identified using Erosion Reference Units (ERefU) and Erosion Response Units (ERU) concepts. In addition, it has also been useful to identify whether the land use suitability in relation to regions is affected by erosion because the ERU permits the evaluation of those critical areas for different land uses. Consequently, the high potential for the identification of ERU can be systematically enhanced in similar studies, having a closer look at parameters and scale.

This study has presented an application of a GIS technique, based on the interactions among geographic factors, which is capable of providing a degree of accuracy in assessing the suitability of landscapes for sustainability of human and natural uses. Thus, improvements in these kinds of analysis are critical issues for land planners not only for making a decision modelling framework, but also in the interpretation of holistic data of a specific region.

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# APPENDICES

Appendix table 1. Peer comparison matrix between parameters

| | ERefU | Topography | Land use | Soil texture | Lithology |
|---|---|---|---|---|---|
| ERefU | 1 | 3 | 4 | 4 | 4 |
| Topography | 0.33 | 1 | 3 | 3 | 3 |
| Land use | 0.25 | 0.33 | 1 | 1 | 1 |
| Soil texture | 0.25 | 0.33 | 1 | 1 | 1 |
| Lithology | 0.25 | 0.33 | 1 | 1 | 1 |

| Parameter | Importance |
|---|---|
| ERefU | 0.464209 |
| Topography | 0.248861 |
| Land use | 0.0956434 |
| Soil texture | 0.0956434 |
| Lithology | 0.0956434 |
| Total | 1 |

Consistency Ratio (CR): 0.023

Appendix table 2. Peer comparison matrix between current erosion categories (ERefU)

| | Very slight | Slight | Moderate | Severe | Very severe |
|---|---|---|---|---|---|
| Very slight | 1 | 0.5 | 0.33 | 0.25 | 0.2 |
| Slight | 2 | 1 | 0.5 | 0.33 | 0.25 |
| Moderate | 3 | 2 | 1 | 0.5 | 0.33 |
| Severe | 4 | 3 | 2 | 1 | 0.5 |
| Very severe | 5 | 4 | 3 | 2 | 1 |

| Category | Importance of category | Importance of parameter | Total weight (category * parameter) |
|---|---|---|---|
| Very slight | 0.0617666 | 0.464209 | 0.028673 |
| Slight | 0.0972536 | 0.464209 | 0.045146 |
| Moderate | 0.159923 | 0.464209 | 0.074238 |
| Severe | 0.262518 | 0.464209 | 0.121863 |
| Very severe | 0.418539 | 0.464209 | 0.19429 |

Appendix table 3. Peer comparison matrix between topographic erodibility categories

| | Very weak | Weak | Moderate | Strong | Very strong |
|---|---|---|---|---|---|
| Very weak | 1 | 0.5 | 0.33 | 0.25 | 0.2 |
| Weak | 2 | 1 | 0.5 | 0.33 | 0.25 |
| Moderate | 3 | 2 | 1 | 0.5 | 0.33 |
| Strong | 4 | 3 | 2 | 1 | 0.5 |
| Very strong | 5 | 4 | 3 | 2 | 1 |

| Category | Importance of category | Importance of parameter | Total weight (category * parameter) |
|---|---|---|---|
| Very weak | 0.0617666 | 0.248861 | 0.015371 |
| Weak | 0.0972536 | 0.248861 | 0.024203 |
| Moderate | 0.159923 | 0.248861 | 0.039799 |
| Strong | 0.262518 | 0.248861 | 0.06533 |
| Very strong | 0.418539 | 0.248861 | 0.104158 |

Appendix table 4. Peer comparison matrix between land use erodibility categories

| | Weak | Moderate | Strong | Very strong |
|---|---|---|---|---|
| Weak | 1 | 0.5 | 0.33 | 0.25 |
| Moderate | 2 | 1 | 0.5 | 0.33 |
| Strong | 3 | 2 | 1 | 0.5 |
| Very strong | 4 | 3 | 2 | 1 |

| Category | Importance of category | Importance of parameter | Total weight (category * parameter) |
|---|---|---|---|
| Weak | 0.095435 | 0.0956434 | 0.009128 |
| Moderate | 0.160088 | 0.0956434 | 0.015311 |
| Strong | 0.277181 | 0.0956434 | 0.026511 |
| Very strong | 0.467296 | 0.0956434 | 0.044694 |

Appendix table 5. Peer comparison matrix between soil texture erodibility categories

| | Very weak | Weak | Moderate | Strong | Very strong |
|---|---|---|---|---|---|
| Very weak | 1 | 0.5 | 0.33 | 0.25 | 0.2 |
| Weak | 2 | 1 | 0.5 | 0.33 | 0.25 |
| Moderate | 3 | 2 | 1 | 0.5 | 0.33 |
| Strong | 4 | 3 | 2 | 1 | 0.5 |
| Very strong | 5 | 4 | 3 | 2 | 1 |

| Category | Importance of category | Importance of parameter | Total weight (category * parameter) |
|---|---|---|---|
| Very weak | 0.0617666 | 0.0956434 | 0.005908 |
| Weak | 0.0972536 | 0.0956434 | 0.009302 |
| Moderate | 0.159923 | 0.0956434 | 0.015296 |
| Strong | 0.262518 | 0.0956434 | 0.025108 |
| Very strong | 0.418539 | 0.0956434 | 0.04003 |

Appendix table 6. Peer comparison matrix between lithology erodibility categories

| | Very weak | Weak | Moderate | Strong |
|---|---|---|---|---|
| Very weak | 1 | 0.5 | 0.33 | 0.25 |
| Weak | 2 | 1 | 0.5 | 0.33 |
| Moderate | 3 | 2 | 1 | 0.5 |
| Strong | 4 | 3 | 2 | 1 |

| Category | Importance of category | Importance of parameter | Total weight (category * parameter) |
|---|---|---|---|
| Very weak | 0.095435 | 0.0956434 | 0.009128 |
| Weak | 0.160088 | 0.0956434 | 0.015311 |
| Moderate | 0.277181 | 0.0956434 | 0.026511 |
| Strong | 0.467296 | 0.0956434 | 0.044694 |