Modelling environmental variables for geohazards and georesources assessment to support sustainable land-use decisions in Zaragoza (Spain)

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Abstract

Land-use decisions are usually made on the basis of a variety of criteria. While it is common practice to integrate economic, ecological and social (triple bottom line) criteria, explicit geoscientific factors are relatively rarely considered. If a planned land-use involves an interaction with the geosphere geoscientific aspects should be playing a more important role in the process. With the objective to facilitate a sustainable land-use decision making a research project was initiated. The area around the city of Zaragoza, in the Ebro Basin of northern Spain, was chosen due to its high degree of industrialisation and urbanisation. The area is exposed to several geohazards (e.g., sinkholes and erosion) that may have significant negative effects on current and future land uses. Geographical Information System (GIS) technologies are used to process the complex geoscientific information. Further GIS analysis comprised the creation of an erosion susceptibility map that follows the ITC (International Institute for Geo-Information Science and Earth Observation) system of terrain analysis. The agricultural capability of the soil was determined using the Microleis System. We identify geomorphologic units that show high susceptibility to erosion and high agricultural potential and suggest a method to implement this information in a land use planning process. Degraded slopes developed upon Tertiary rocks show the highest susceptibility to erosion and low values of agricultural capability, whereas the flat valley bottoms and irrigated flood plains have the highest values of agricultural capability.

Keywords: erosion susceptibility; agricultural capability; GIS; Ebro Basin; Spain

1 Introduction

One of the principal challenges for the 21st century is supporting the sustainable development of large cities. However, the relationship between economic development and environmental sustainability is complex. For instance due to the rapid pace of urban development, interactions with the geosphere have largely been ignored in the peripheral parts of Zaragoza city (Figure 1). This development has led to the destruction of significant infrastructure due to land subsidence, the misuse of valuable agricultural land, the destruction of valuable natural areas, and an increasing contamination of aquifers. The United Nation's Agenda 21 (http://www.un.org/esa/sustdev/) suggests that all countries should undertake an appropriate national inventory of their land resources, establish a land information system, classify land resources according to their most appropriate uses, and identify environmentally fragile or disaster-prone areas for special protection measures. Although land-use decisions are usually made on the basis of triple bottom line criteria, geoscientific aspects are rarely considered or are regarded as being of less importance (Marker, 1998; Hoppe et al., 2006). However, most georesources, especially raw materials, are inherently non-renewable resources; if we use these resources today, future generations cannot use them again. The consideration of geoscientific aspects therefore deserves more attention.

To fulfil land management functions, the tools to be used must be updatable, multiscalar, and contain a wide rage of data concerning the environment; i.e., physical, biotic, and anthropogenic aspects and their interrelations. From this viewpoint, a geographic information system (GIS) is required (Amadio et al., 2002). In recent years, the development of Spatial Decision Support Systems (SDSS) has proved to be a considerable aid in efforts to solve the land-use conflicts that commonly arise in sustainable land-use management schemes. Such systems combine the benefits of GIS tools and decision support techniques, making them suitable in supporting the sustainable development of urban areas via land-use suitability analysis. Based on the above, the area surrounding Zaragoza, which represents a large and growing urban nucleus, merits closer investigation in terms of geoscientific factors. Thus, a research project was initiated which main objective was the development of a methodology, which will facilitate the geohazards and georesources assessment and the decision-making of different land-use forms under geoscientific aspects in a semiarid environment as the Ebro Basin, in the surroundings of Zaragoza. It was our aim to perform a land-use suitability analysis to identify the most appropriate pattern for future land uses, according to specify preferences to maintain a sustainable development. Fulfilling this main objective implies that diverse secondary objectives must be carried out. These are:

- Characterization of the study area and collection, analysis and treatment of available information for its introduction into a GIS environment.
- Geohazards and georesources detection, description and modelling with the help of GIS and 3D techniques (when no previous models exist). The final objective of these models is to serve as criterion maps for the land-use suitability analysis.
- Land-use suitability analysis by means of SDSS.

Figure 2 shows the project workflow. The first step involved the gathering of as much information as possible regarding factors such as geology, geomorphology, soils, vegetation, and land use; this information was then entered into a GIS. The land was then evaluated with respect to the geohazards of erosion, doline susceptibility, and groundwater vulnerability (see Lamelas et al., 2007a, 2008), as well as with respect to georesources consisting of sand and gravel deposits (Lamelas et al., 2007b), agricultural capability, and other resources such as natural areas that are of value from an environmental and scientific viewpoint because the environment contains essential habitats for the conservation of species that in some cases are in danger of extinction. Different models at a regional scale (between 1:50,000 and 1:100,000) were developed using different methodologies to evaluate hazards and resources. The different models were then used as spatial criteria (criterion map) in a decision support system (DSS) and integrated into a GIS (Lamelas, 2007; Lamelas et al., 2007b), thereby forming a SDSS that provides various suitability maps for different land-use forms (sand and gravel extraction, irrigated land, industrial areas and urbanization).

In the present study, we report on one of the secondary objectives, modelling of geoscientific aspects of erosion susceptibility and agricultural capability using diverse land use evaluation methodologies. 3D modelling techniques have been used for groundwater vulnerability, doline susceptibility assessment and sand and gravels deposits evaluation (e.g. Hoppe et al. 2006; Lerch and Hoppe, 2007; Lamelas et al., 2007a,b, 2008). However, in the following sections we would like to explain in more detail the general methodology of the project as it extremely determines the development of the above mentioned models.

1.1 Data collection

As a first stage, all of the information regarding factors such as geology, geomorphology and hydrogeology, land cover, soil properties, climate, infrastructure, protected areas, and areas worth protecting was collected and integrated into the GIS database ArcGIS 9.1 (ESRI, 2005). The type of data to be collected depends on the objectives of the study, and these objectives may change over time, thereby determining the dynamic nature of data collection. At this stage, an appropriate conceptualisation of the GIS database is of great importance. The compilation of information includes the tasks of searching for the best information available, analysing its characteristics, introducing information into a GIS, and creating new digital information by digitising paper maps or analysing aerial photographs. A parallel task is the gathering of methodologies for land evaluation modelling.

1.2 Georesources and geohazards modelling -Selection of land evaluation methodologies

Models are considered as simplified representations of the real world that can be expressed in a wide variety of forms, including conceptual diagrams, classification systems, and statistical or deterministic mathematical models. In land evaluation, empirical-based modelling has advanced over time from simple qualitative approaches to artificial intelligence techniques (de la Rosa et al., 2004). The primary requirement of simulation modelling is that the model input parameters be accurately quantified. Model input data can be obtained either directly from field measurements or sourced from the existing literature (Cox and Madramootoo, 1998). The development of GIS has greatly expanded the possible applications of land evaluation modelling, and many different approaches have been described since the end of the 1970s. However, land evaluation modelling requires the preliminary selection of a suitable mapping unit (Burrough, 1986; Saura, 2002). At the scale of analysis, a mapping unit represents a domain that maximises internal homogeneity and inter-unit heterogeneity. The various methods that have been proposed to divide the terrain in mapping units for land evaluation modelling can be categorised into the following groups (Meijerink, 1988; Tomlin, 1990; Guzzetti et al., 1999):

- Grid-cells, preferred by raster-based GIS users, divide the territory into regular squares of pre-defined size which become the mapping unit of reference.

- Terrain units, traditionally favoured by geomorphologists, are based on the observation that, in natural environments, the interrelations between materials, forms and processes result in boundaries which frequently reflect geomorphological and geological differences.
- Unique-condition units imply the classification of different characteristics of the land into a few significant classes which are stored into a single map, or layer. By sequentially overlying all the layers, homogeneous domains (unique conditions) are singled out whose number, size and nature depend on the criteria used in classifying the inputs.
- Slope-units, automatically derived from high-quality Digital Topographic Models, partition the territory into hydrological regions between drainage and divide lines.

The different land evaluation procedures can be classified in two main groups: qualitative and quantitative methods (Figure 3). The former group includes qualitative approaches, expert systems, and parametric systems. Such methods are very flexible, and permit the complete inclusion of expert knowledge; unfortunately, they also involve a high degree of subjectivity, meaning that the maps produced by different researchers may be wildly different. Quantitative methods include statistical modelling and recent approaches based on neural networks. Although a completely objective procedure does not exist, the use of quantitative methods ensures that reproducible results can be achieved provided that the same basic assumptions are made (Guzzetti et al., 1999; Beguería and Lorente, 2003; de la Rosa et al., 2004). Both types of methods have their advantages and disadvantages; thus, the choice between quantitative and qualitative approaches should be based on several factors, including the availability and quality of information relevant to the models development, the possibility of obtaining information for their validation, the adequacy of the information in terms of the study area, and the final objective of the models. In the case of the present study, the final objective of the models is to serve as criterion maps in a land-use suitability analysis.

1.3 Land-use suitability analysis

The final objective of the project was to perform a land-use suitability analysis. Broadly defined, land-use suitability analysis aims to identify the most appropriate spatial pattern for future land uses according to specified requirements or preferences (Malczewski, 2004). GIS-based land-use suitability analyses have been applied in a wide variety of situations, including ecological and geological approaches, suitability for agricultural activities, environmental impact assessment, site selection for facilities, and regional planning (Malczewski, 2004; Sharifi and Retsios, 2004; Hoppe et al., 2006; Lamelas et al., 2006a,b; Marinoni and Hoppe, 2006). Any planning process must focus on a mix of hard (objective) and soft (subjective) information. The idea of combining the objective (reported facts and quantitative estimates) and subjective elements (opinions of interest groups and decision makers) of the planning process in a computer-based system lies at the core of the concept of SDSS (Booty et al., 2001; Shim et al., 2002; Malczewski, 2004). SDSS can be defined as an interactive, computer-based system designed to support a user or group of users in achieving a greater degree of effectiveness in decision making when solving a semi-structured spatial decision problem (Malczewski, 2004). SDSS also refers to the combination of GIS and sophisticated decision support methodologies, e.g. in terms of multi-criteria analysis techniques (Marinoni, 2005).

In the context of land-use suitability analysis, it is important to differentiate between the site selection problem and the site search problem. The aim of site selection analysis is to identify the best location for a particular activity from a given set of potential (feasible) sites. Where there is no predetermined set of candidate sites, the problem is referred to as site search analysis (Malczewski, 2004). In this project, a pixel size 20x20 m was selected as the map unit for the land-use suitability analysis and both approaches were employed. First, a site search analysis in which each pixel represents a potential site was performed using a simple additive weighting (SAW) method implemented in ArcGIS (Lamelas et al., 2006a). A site selection analysis was then performed employing the PROMETHEE-2 methodology (Brans et al., 1986) and using a set of predefined alternatives (Lamelas et al., 2006b). All of the techniques used in the project were programmed and integrated within ArcGIS 9.1 by Marinoni (2004, 2005).

Despite the existence of a diverse range of methodologies, multicriteria decision-making methods have certain aspects in common. The alternatives represent the different choices of action available to the decision maker, and multiple attributes represent the lowest level of decision criteria. Decision weights are assigned to such attributes (criterion maps), with the weights usually being normalized to add up to one (Gilliams et al., 2005). Figure 4 shows this scheme applied to the site search analysis where alternatives representing the different choices of action available to the decision maker are represented by each pixel. Besides, attributes that represent the lowest level of decision criteria have to be defined. Firstly, spatial constraints, which represent areas under use restrictions have to be identified. These restrictions are usually caused by the presence of other uses or by high value natural areas that are under protection. Next, a variety of triple bottom line factors including geoscientific aspects need to be defined (georesources, geohazards, land management planning, etc.). Finally, a set of criteria weights that reflect the importance of every particular criterion is required. Setting criteria weights is a crucial step for the majority of multi-criteria analysis techniques, including the methods which will be applied in this project. The weights are usually directly determined by a panel of stakeholders in a participatory process. However, criteria weights can also be indirectly determined by means of preference information where stakeholders express their preferences on a numerical scale. One of the most prominent multi-criteria analysis techniques that uses this preference information to compute the needed weights is the Analytic Hierarchy Process AHP (Saaty 1977) which has been used in both of the approaches described above (Lamelas et al., 2006a,b; Lamelas, 2007; Lamelas et al., 2007b).

2 Description of the study region

Zaragoza is the capital of the Region of Aragon, located in the central part of the Ebro Basin, northeast Spain (Figure 1). The city is located within the homonym area in the region of Corredor del Ebro (Ebro Corridor), a highly dynamic and densely populated economic axis within the Iberian Peninsula. Its strategic position in the middle of four of the most important developed areas within the Iberian Peninsula (Madrid, Barcelona, País Vasco, and Valencia), accompanied by the declaration of the city in 1964 as a focus of industrial development (Polo de Desarrollo Industrial), resulted in a marked increase in population in the 1970s to 500,000 inhabitants. Today, the city has a total population of about 700,000 (more than 60% of the total population of the Aragon Region), and this figure is expected to increase even further in the next decade due to the attraction created by the organization of the 2008 EXPO with the theme of Water and Sustainable Development.

2.1 Geological setting

The triangle-shaped Ebro Basin is bound to the north by the Pyrenees, to the southwest by the Iberian Range, and to the southeast by the Catalan Coastal Range. The formation of the basin was determined by the deformation histories of these bounding ranges, which arose as a consequence of Alpine orogenesis (Alberto et al., 1984). The continental sedimentary infill of the basin is composed of conglomerate and sandstone at the basin margins, grading into clay, marl, evaporite, and carbonate facies toward the depocentre (Benito et al., 1998). In the central part of the basin, these playa-lake deposits (Zaragoza Formation) form the largest outcrop of gypsum in the area, divided by the Ebro and Gállego rivers into three sectors: Retuerta, Mediana, and Alfocea (Quirantes, 1978). A proto-Ebro river captured the depression, possibly at the end of the Miocene or beginning of the Pliocene, meaning that the basin lost its endorheic character. During the Quaternary, pediments and terraces developed upon the evaporitic deposits, forming an alluvial aquifer that contributes to active and permanent karst processes.

2.2 Geohazards

Accordingly to Alexander (2000), a hazard is an extreme geophysical event that is capable of causing a disaster. The word 'extreme' in this case signifies a substantial departure in either the positive or negative direction from a mean or a trend. The fundamental determinants of hazards are location, timing, magnitude, and frequency. Many hazardous phenomena are recurrent in time and predictable in terms of location. An important geohazard in the present study region is erosion. In addition to the natural factors of wind and rain, changes in land-use and activities (e.g. pasturing) may lead to increased rates of erosion in the study area. The erosion of slopes involves the detachment and transport of soil particles. The energy required for this process is supplied mainly by raindrop impact, superficial flow, and the combination of these phenomena (Gutiérrez-Elorza and Sancho, 1993). The size and distribution of soil particles, as well as the structure and stability of the soil, are the main properties that determine the susceptibility to erosion in arid regions. A semiarid climate and rainfall distribution dominated by storm events as occur in this area lead to a further increase in the probability of soil loss. Given the high solubility of gypsum, soil erosion can also adversely affect water quality, as the eroded material is transported into superficial flows, thereby increasing their salinity and conductivity. From an environmental viewpoint, both desertification and salinization are serious concerns in the Zaragoza area (Machín and Navas, 1998). The limiting nature of the edaphic and climatic conditions in this area, in combination with poor land management, overgrazing, and deforestation, pose serious problems in terms of surface water quality and soil conservation, especially as the latter is a non-renewable resource. Gullies are the most conspicuous form of erosion in the Mediterranean region. Incising the Tertiary and Quaternary sediments within many valley bottoms, gullies frequently threaten agricultural fields and plantations. In Spain, gullies (*barrancos*) are considered to be the main sediment source responsible for the rapid siltation of reservoirs, which are of vital importance as a source of drinking and irrigation water (Ries and Marzolff, 2003).

2.3 Georesources

Soils suitable for agricultural use are important georesources in the Zaragoza area. The most abundant soils in the study area are fluvisols and calcisols located upon river terraces, regosols developed upon unconsolidated gypsiferous colluvial material, cambisols located upon low pediments, and gypsisols developed upon alluvial/colluvial gypsiferous materials. Soils can be used for almost any agricultural purpose if sufficient inputs are supplied. External inputs or improvements are expressed in terms of capital, energy, or environmental costs. The main aim of soil protection is to minimise these socio-economic and environmental costs by predicting the inherent capacity of a soil unit to support a specific soil use and managing the soil over a long time period without deterioration (de la Rosa et al., 2004). The soil resource has been threatened in recent decades by the widespread construction of infrastructure upon low river terraces that have traditionally been occupied by long-established orchards. Moreover, the fragility of the soils makes it essential to obtain information on the intrinsic capacity of the soils to sustain different agricultural uses if we are to conserve and maintain the landscape.

3 Methodology

As mentioned above, this article concentrates on land evaluation methodologies for erosion susceptibility and agricultural capability modelling. With respect to agricultural capability, the first methods developed for land evaluation, after the FAO scheme (FAO, 1976), were mainly oriented toward edaphologic components. Subsequently, more economic-based approaches were developed because a specific use is normally determined by economic parameters. Current models tend to be more crop-oriented. A comprehensive review of the different methodologies can be found in Santé and Crecente (2005). Most of the examples of the general modelling of agricultural capability using GIS are developed from the establishment of terrain units of unique conditions. Cendrero et al. (1990) developed maps of homogeneous integrated units for the Mediterranean province of Valencia and Gran Canaria (Spain). The morphodynamic units were then evaluated in terms of their soil capability and other qualities significant for planning. De la Rosa and Magaldi (1982) developed the Cervatana Model (de la Rosa et al., 2002, 2004; CSIC, 2004), which forecasts the general land-use capability or suitability for a broad series of possible agricultural uses. The spatial unit of the study of reference is the land-unit, which is defined based upon both the intrinsic characteristics of the soil and other ecological aspects such as the macro topography, climate, current use, and vegetation (de la Rosa et al., 2004). This model was selected in the present study for assessing the agricultural capability of soils.

In recent decades, many approaches have been developed to establish an erosion hazard model using GIS (Kertész, 1993; Cyr et al., 1995; Cox and Madramootoo, 1998; Le

Bissonnais et al., 2001). A good example is that proposed by Cox and Madramootoo (1998), who developed a soil loss model within a GIS environment for St. Lucia to evaluate (in terms of soil loss) agricultural management strategies developed for two agricultural watersheds. Most models are based on the universal soil loss equation (USLE) methodology (Wischmeier and Smith, 1978) and subsequent derivations such as RUSLE and USLE-M (Renard and Freimund, 1994; Cox and Madramootoo, 1998; Kinnell, 2001; Shi et al., 2004). USLE is an empirical model developed by Wischmeier and Smith (1978) to predict long-term average annual soil loss from agricultural fields. The model integrates the following six parameters that influence soil loss: average annual soil loss rate; rainfall erosivity; soil erodibility; slope length of the terrain; slope steepness; crop management and conservation practices. This methodology has also been widely used in European countries. On a continental scale, the CORINE (Coordination of Information on the Environment) program of the European Commission developed an erosion risk map based on the USLE methodology (Wischmeier and Smith, 1978). Another approach was developed by ICONA (1987) for the Ebro Basin on a 1:400,000 scale; however, some authors, such as Desir (2001), find that this methodology overestimates the erosion rates when compared with experimental data. ICONA (1987) obtained erosion rates of 200 t/ha/year for the gypsum slopes of the central Ebro Basin using USLE methodology, while Navas (1988) calculated values of 81.7 t/ha/year for salts transported from the Ebro Basin to the Mediterranean Sea. Renschler and Harbor (2002) noted the inconvenience of using this method if applied in areas having different characteristics to those for which the method had been developed, as is the case when applying the method in Mediterranean regions. Mati et al. (2000) concluded that USLE (Wischmeier and Smith, 1978) underestimates or overestimates the amount of erosion depending on the extent of vegetation cover.

Taking these factors and the objective of this study (determining the optimal locations for different land uses) into account, it was decided to use a qualitative weighting method to differentiate between strongly and weakly susceptible areas, but not to quantify the amount of eroded material. Thus, we employed the methodology developed by van Zuidam and van Zuidam-Cancelado (1979), who studied in detail the geomorphology of the central Ebro Depression.

The selected erosion susceptibility and agricultural capability models require the prior determination of homogeneous units. Thus, before describing the modelling approach, we consider the method employed in discriminating homogeneous units.

3.1 Division in homogeneous units and soil mapping

Some of the properties of soil are indispensable factors in terms of erosion processes and agricultural capability. The lack of a detailed soil map of the study area adds additional value to the homogeneous unit division because it enables the identification of morphoedaphic units, or soil mapping.

The formation of a soil depends on several landscape factors; consequently, following a geosystems concept, the establishment of different landscape units that are homogeneous with respect to the relevant landscape factors, enables the development of a map of morphoedaphic or geoedaphic units (Saz-Gonzalvo, 2001). Amadio et al. (2002) emphasized the importance of geomorphology in studies of landscape ecology. In fact, at the regional scale their findings suggest that physiography provides the best approximation of the results of a landscape classification undertaken following a holistic approach. Thus, the regional scale of the analysis means that geomorphology is selected as the main criterion for division. The units depicted in 1:50,000 geological maps compiled by the National Geological Institute (ITGE, Instituto Tecnológico y Geológico de España) were reclassified into seven categories (Table 1). The structural platforms were included in the degraded relief of Tertiary sediments due to their limited extent. Glacis and alluvial fans were combined as a result of their shared colluvial origin and lithological similarity. The endorheic areas, despite being of limited extent, were kept as a single category because of their exceptional soils. Land cover was used as a second criterion. The CORINE 1:100,000 Land Cover Map of 2004 (Table 2) was also reclassified. The resulting five categories were grouped, as in the case of the geological map, taking into account the final destination: mapping of morphoedaphic units, assessing the agricultural capability of the soils, or erosion susceptibility modelling. Consequently, all human infrastructure was grouped in a unique category and the forest category was combined with irrigated land due to its limited extent, which is almost always linked to the locations of rivers and areas proximal to irrigated land.

Finally, both reclassified cartographies were superimposed and the result of the intersection and integration of the two maps was the following set of fourteen homogeneous units (Figure 5) mapped at a scale between 1:50,000 and 1:100,000:

- Flood plain with non-irrigated arable land and sclerophyllous vegetation.
- Flood plain with permanently irrigated land and forest.
- High terraces with non-irrigated arable land.
- High terraces with permanently irrigated land.
- High terraces with sclerophyllous vegetation.
- Flat valley bottoms with non-irrigated arable land.
- Flat valley bottoms with sclerophyllous vegetation.
- Glacis and alluvial fans with non-irrigated arable land.
- Glacis and alluvial fans with permanently irrigated land.

- Degraded slopes developed upon Tertiary material with sclerophyllous vegetation.
- Degraded slopes developed upon Tertiary material with non-irrigated arable land.
- Endorheic areas with permanently irrigated land.
- Water bodies.
- Human infrastructure.

Many authors have stated that the existence of different geomorphologic units enables differentiation into several soil groups (Albareda et al., 1961; Alberto et al., 1984; Desir, 2001). Therefore, the geomorphologic component of the landscape units determines the type of soil assigned to the homogeneous units. The final assignment of soils to different homogeneous units (Table 3; Figure 6) was based on a revision of previous studies undertaken in the study area. Alberto et al. (1984) studied the Quaternary deposits of the Ebro Basin in the Aragón region, producing a 1:200,000 soil map. In addition, a 1:250,000 soil map was produced by the National Centre of Scientific Investigations (CSIC, 1970) and a number of soil maps were included in the 1:200,000 National Forest Map produced by the Institute for Nature Conservation (ICONA, 1990). Following the most recent version of the FAO classification (FAO, 1998), the study area presents the following six types of soils: calcaric fluvisols, petric calcisols, haplic gypsisols, calcaric cambisols, calcaric regosols, and haplic solonchaks.

3.2 General agricultural capability

The general agricultural capability of the soil was defined using the Cervatana Model (de la Rosa et al., 2002, 2004; CSIC, 2004). This model, which is a component of the MicroLEIS system (Mediterranean Land Evaluation Information System), was developed by de la Rosa and Magaldi (1982). Since the 1990s, this system has evolved into an agro-ecological decision support system. Today, MicroLEIS DSS is a set of useful tools for decision making within a wide range of agroecological schemes, and is available from: http://www.microleis.com (de la Rosa et al., 2004). The prediction of general land-use capability is the result of a qualitative evaluation process or an overall interpretation of the following biophysical factors: relief, soil, climate, and current land use or vegetation (Figure 7). The most important aspects of such an evaluation system can be summarized as follows (CSIC, 2004):

- The spatial unit of the study of reference is the land unit.
- Prediction of the potential land-use capability is not contemplated after major improvements or developments such as irrigation or desalinisation.
- Socio-economic factors that affect productive processes are not considered, as this is exclusively a system of biophysical evaluation.
- The land units are grouped into four classes. The first three -S1, S2, and S3- include land considered capable of supporting continuing, intensive agricultural use, while land class N is more appropriate for farming or forestry.
- Appropriate sub-classes are established depending on the selected limiting factors: site, soil, erosion risk, and bioclimatic deficiency.
- The procedure of maximum limitation is used, with matrices of degree, to relate the land characteristics directly with the classes of use capability.

Table 4 shows an example of a matrix of degree (in this case, for the factor of 'site'), which is determined by the slope. The classes were assigned to every homogeneous unit using the tool zonal statistics in ArcGIS (applied to both homogeneous units) and information obtained from a digital elevation model produced by the Ministry of

Agriculture (pixel size, 20 × 20 m; MAPA, 1997). Table 3 shows the mean slope value and the capability class assigned to each homogeneous unit according to the slope. Besides, for the model development it is required the determination of some characteristics of the different soil types (texture, rock content, useful depth, drainage, and salinity). As it was not possible to carry out a soil analysis campaign, in order to determine the required information, we revised detailed studies carried out previously in the proximity of the present study area. Machín and Navas (1994, 1995, 1998) studied the soils and their agricultural capability and performed several soil analysis. Thus, the derived values of the soil properties obtained by them were used for the model development. Table 3 presents the values assigned to each homogeneous unit according to the properties data for the different soils sourced from previous studies. Four variables determine the erosion risk as limiting factors for good agricultural capability. Table 5 shows the matrix of degree of capability for these four factors (erodibility of the soils, slope, vegetation density, and rain erosivity) with values adapted from the CORINE project. The soil erodibility is considered to be low in soils with more than 0.75 m of useful depth, silty texture, and more than 10% rock content. Moderate erodibility is assigned to soils with between 0.25 and 0.75 m of useful depth, well-balanced or sandy texture, and less than 10% rock content. Finally, high erodibility is assigned to soils with less than 0.25 m of useful depth, silty texture, and less than 10% rock content. Table 3 lists the values of capability assigned to each homogeneous unit. The same value of rain erosivity has been given to all units, with values based on data from the Ministry of Agriculture for the agro-climatic characterization of the area of Zaragoza (MAPA, 1987).

The degree matrix for bioclimatic deficiency was developed according to the Terraza model (CSIC, 2004), which was also created for the MicroLEIS system. The aridity is expressed as the ratio of annual precipitation to annual evapotranspiration. According to the agro-climatic characterization of Zaragoza Province, annual precipitation is about 350 mm in the study area and evapotranspiration is about 850 mm, thereby yielding an aridity index of 0.41. Thus, all the study area is assigned a moderate agricultural capability with respect to the aridity factor (Table 3). Frost risk is assigned according to the number of months in the year with mean minimum temperatures of less than 6 °C. According to the agro-climatic characterization, Zaragoza experiences between 4 and 6 months with mean minimum temperatures of less than 6 °C; therefore, all of the homogeneous units are considered to have good agricultural capability with respect to frost risk.

As stated above, the procedure of maximum limitation is used in assigning the final agricultural capabilities; thus, each homogeneous unit is assigned the agricultural capability of the most limiting factor (Figure 8).

3.3 Erosion susceptibility model

As mentioned above, the employed methodology was developed by van Zuidam and van Zuidam-Cancelado (1979), who proposed an "ITC system of terrain analysis, classification and evaluation" based on a landscape zoning approach. The terrain is divided into terrain units or landscape units, and the parameters, as well as land qualities, may be rated, evaluated, and classified employing aerial photographs, various thematic maps (e.g., topographic and soil maps), field data, and expert knowledge. Thus, in the present study the homogeneous units created for the morphoedaphic cartography were used for the erosion susceptibility model.

The following parameters introduced in the model match those used in the majority of previous approaches (Wischmeier and Smith, 1978; ICONA, 1987; Kertész, 1993;

Renard and Freimund, 1994; Cyr et al., 1995; Cox and Madramootoo, 1998; Kinnell, 2001; Le Bissonnais et al., 2001; Shi et al., 2004):

- Slope: slope steepness, slope length, slope form.
- Vegetation/Land-use: vegetation density, land-use condition.
- Climatologic conditions: frequency of heavy rainstorms.
- Erosion and mass movement rating: rating of wind erosion; rating of sheet erosion; rating of rill, gully, and ravine erosion; rating of mass movement hazard.
- Soil/Geology: depth of unconsolidated material, texture, sealing susceptibility, consolidation and/or jointing rate of the subsoil, structure of underlying strata, depth of impermeable layer below the surface.
- Conservation practices: in plain, in drainage ways.

Each terrain parameter must be classified and rated. A summation of the ratings is then made, and landscape units are classified according to their erosion susceptibility. The different terrain units are classified with respect to the slope, according to slope steepness, length, and shape. Tables 6 and 7 show the ratings given to every class, according to slope steepness and slope length, respectively (van Zuidam and van Zuidam-Cancelado, 1979). With respect to slope shape, concave, convex and straight slopes are assigned values 1, 2 and 3, respectively. Table 8 shows the rating assigned to each unit in the present study. The slope steepness was evaluated following the procedure used for agricultural capability; the zonal statistic tool was applied to every homogeneous unit (see Table 3 for slope percentage of every unit). Because of the diversity of slope lengths within each homogeneous unit and the difficulty of assigning a single value for every unit, a slope length value of 4 (moderately long) was assigned to all of the units. For slope shape, we used the description by Alberto et al. (1984) of the different Quaternary geomorphologic units of the Ebro Depression, as well as by expert knowledge. Thus, almost all of the units, such as the flood plain and degraded slopes, present straight slopes, while the glacis and alluvial fans present convex slopes, and the endorheic areas, concave slopes.

In accordance with van Zuidam and van Zuidam-Cancelado (1979) the ratings for the vegetation/cover factor can be assigned consistent with either vegetation density data or land-use condition data. In this case, we used land cover data sourced from CORINE, since this factor was also used for the division in homogeneous units. Table 9 shows the ratings assigned to different vegetation density and land-use condition classes (van Zuidam and van Zuidam-Cancelado, 1979). The ratings assigned to the homogeneous units based on the description provided by CORINE cartography can be observed in Table 8. The adaptation of these values to the descriptions and ratings assigned by van Zuidam and van Zuidam-Cancelado (1979) was performed on the basis of the results of studies undertaken in the areas surrounding the present study area (Desir, 2001; Ries, 2002). Thus, irrigated land and forest are assigned the lowest ratings, given their low susceptibility to erosion, and dry arable land is assigned the highest ratings, even higher than those for sclerophyllous vegetation, possibly because of the existence of a lichen crust upon soils in areas occupied by shrubs.

The factor climate was classified on the basis of heavy rainstorm frequency. If it is exceptional, one a year or several times a year, it is assigned value 1, 2 and 4, respectively. In this case, the entire study area is assigned a value 4 because heavy rainstorms occur more than once a year (van Zuidam and van Zuidam-Cancelado, 1979).

Four different variables are analysed in assigning ratings for the erosion and mass movement factors: the rating of wind erosion; sheet erosion; rill, gully, and ravine erosion; and the mass movement hazard rating (van Zuidam and van Zuidam-Cancelado, 1979). Firstly, the rating of wind erosion, according to this method, can be classified on the basis of the presence or absence of an A horizon in the soil profile and its textural characteristics. But, in addition to this characteristic, it was classified on the basis of the slope or verticality of the surface and elevation, with respect to the surrounding areas, which influences the possibility of the soil being affected by wind erosion. Table 10 shows the rating for the different classes with respect to the four erosion and mass movement factors (van Zuidam and van Zuidam-Cancelado, 1979). Secondly, sheet erosion is classified according to the presence of evidence of erosion in the soils, as well as the presence or absence of an A horizon. For instance, the presence of a well-developed A horizon is evidence of no sheet erosion (rating 0, according to Table 10), and the absence of A horizon is evidence of severe sheet erosion (rating 4, according to Table 10) (van Zuidam and van Zuidam-Cancelado, 1979). The third factor, rill, gully and ravine erosion, is classified according to the depth and frequency of rills in the terrain (van Zuidam and van Zuidam-Cancelado, 1979). Finally, the last factor is mass movement hazard rating. Table 10 shows the classes and ratings for this factor, assigned according to the existence of this phenomenon and the extent of surface affected by it (van Zuidam and van Zuidam-Cancelado, 1979). Table 8 shows the rating assigned to every homogeneous unit with respect to the erosion factors, which was controlled by air photographs analysis, field work and expert knowledge. The degraded slopes present the highest values in every erosion factor, especially in sheet and rill erosion factor. In the case of the flat bottom valleys, it is important to stress the highest rating in relation to gully erosion. Mass movements are only present in degraded slopes in Tertiary materials, mainly in the scarps in the north of the study area and also, but less frequently, in the walls of the gullies developed in the flat bottom valleys. The high frequency of strong winds in the study area determines the absence of values 0 in the homogeneous units. The ratings assigned to these factors may give an idea of the dominant erosion process present in every landscape unit. Consequently, in the terraces, the most dominant erosion process is caused by sheet and wind erosion; in the flat bottom valleys, gully erosion is the leading process; and in the degraded slopes, all the processes are important, but with a higher rill erosion and sheet erosion significance.

With respect to soil, erosion is rated on the basis of useful depth, texture, sealing susceptibility, and consolidation. Tables 11, 12, 13 show the ratings assigned to useful depth, texture and sealing susceptibility class (van Zuidam and van Zuidam-Cancelado, 1979). In relation to consolidation factor, firmly, weekly and Non-consolidated soils are assigned values 1, 2 and 4, respectively. In order to assign the different ratings to the terrain units, the soil properties analysis and descriptions obtained from previous studies undertaken in the area by Machín and Navas (1994, 1995, 1998) were used. These ratings can be observed in Table 8.

In relation to geology, we assessed the structure of underlying strata and the depth of impermeable layers below the surface. In the case of the structure of underlying strata, the entire study area is assigned a value of 0, which corresponds to horizontally bedded strata (Table 14). For the depth of impermeable layers below the surface, almost the entire area is assigned a value of 0 because the gypsum formation forms an impermeable layer throughout the study area, and the overlying Quaternary cover is usually deeper than 1.5 m. Exceptions to this are areas of degraded relief, where the gypsum strata are covered only by regosols with useful depths of less than 0.5 m (Table 15).

The conservation practices factor refers to agricultural practices adopted to mitigate erosion. The two different factors considered here are conservation practices in plain areas (Table 16) and conservation practices in drainage ways (Table 17). Both factors are assigned negative values (Table 8) in relation to their ability to reduce erosion susceptibility (van Zuidam and van Zuidam-Cancelado, 1979). In relation to practices in plain, all the irrigated areas attain value –4, due to the presence of contour terracing. Besides, these areas also obtain value –2 with respect to conservation practices in drainage ways because of the presence of canals.

As explained above, the ratings of all factors are summed to obtain the final erosion susceptibility value (see Table 8; Figure 9).

4 Results

With respect to the agricultural capability of soils, most of the study area is assigned to class S3: land with moderate use capability and with a limiting climate factor (Figure 8). According to the Cervatana model, the presence of these areas acts to substantially reduce the range of possible crops and productive capability. Management techniques in such areas are more difficult to apply and maintain, with higher costs. Intensive practices, and sometimes special conservation practices, are necessary to maintain continued productivity. The degraded areas in Tertiary gypsum with arable land are also classified as moderately capable; however, in this case both the soil and climate are limiting factors. Slope is an additional limiting factor in degraded areas covered by sclerophyllous vegetation. Finally, the endorheic areas are assigned to class N (marginal or non-productive land).

In terms of erosion susceptibility, degraded slopes developed upon Tertiary sediments with irrigated land or sclerophyllous vegetation present the highest susceptibility values, due mainly to their high scores in terms of the soil, slope, and erosion factors. Flat valley bottoms covered by non-irrigated arable land or sclerophyllous vegetation also present a high degree of erosion susceptibility, reflecting the unfavourable characteristics of the soil and slopes. In this case, gully erosion is the main erosion process (Figure 9). The lowest susceptibility to erosion is recorded by flood plains, high terraces, and pediments covered by irrigated land and forest, reflecting the lowest values in the land cover factor and the conservation practices factor.

5 Discussion and conclusions

The main objective of this project was to develop a methodology in order to assess, record and map geohazards and georesources which will facilitate the decision-making of different land-use forms under geoscientific aspects, in a semi-arid environment in the surroundings of growing cities, exemplified by Zaragoza. In this respect, the project workflow can serve as a methodological approach to support the sustainable development in developing and growing cities.

In this methodological workflow, a tedious and extremely important part is the data gathering and implementation of the dedicated GIS. The information characteristics and quality as well as the subsequent processing within the GIS might determine the land evaluation methodologies to be used in the land evaluation analysis and, as a consequence, have an effect on the quality of the final geohazards and georesources models. Thus, the selection of the land evaluation methodologies should take into account several factors, i.e. the availability and quality of information for their development, their adequacy to the study area, the availability of information or possibility of performing a field work campaign in order to validate the models, and the final objective of these models.

In general, quantitative approaches involve a lower level of subjectivity. They assure that the same results can be achieved by different researchers provided that the same basic assumptions are made. However, completely objective procedures do not exist and, sometimes, qualitative approaches are more flexible and permit a complete inclusion of expert knowledge. Both types of methodologies have their advantages and disadvantages. Thus, the selection between quantitative and qualitative approaches should be based on the factors mentioned above.

In the project workflow it is not contemplated the creation of new data by means of field work, experimental analysis and so on, unless it is absolutely necessary. For example, the measurement of erosion is a tedious work that it takes several years and it was not possible to include this long process in our general project workflow. On the contrary, our project requires the data collection and the inclusion of the results of experimental studies previously performed in the study area in order to develop the models and to check that our results match theirs. Thus, the lack of a detailed soil map of the study area, at the scale of analysis, determined the creation of a morphoedaphic unit map as certain soil properties are indispensable in determining agricultural capability and erosion susceptibility. The compiled map implied the determination of unique-condition units or homogeneous units, influencing, in this way, the selection of the land evaluation methodologies to be used. Nevertheless, although the morphoedaphic unit map was of great value for our objective, in order to improve upon the results of our investigation and aid future studies that require soil information (i.e., data regarding erosion, groundwater protection, agricultural capability, geotechnical characteristics, etc.), an effort should be made to characterize and map, at a more detailed scale, the soils in areas for which this information is limited. This is an important component of land-use management because the soil supports all of the varied land uses.

The lack of detailed information on erosion and agricultural capability of soils all over the study area and the impossibility of undertaking a field work campaign in order to validate the models influenced also the selection of well-known methodologies previously applied with success in the surroundings of the study area. As mentioned above, the Cervatana model is a valuable methodology in assessing the general agricultural capability of soil that was developed based on Mediterranean data and had already been successfully applied in the area surrounding the present study site at a coarser scale. In the case of the erosion susceptibility, the ITC system of terrain analysis was selected because it had previously been successfully applied in the present study area. Besides, the most commonly applied method, the quantitative USLE approach (Wischmeier and Smith, 1978), was rejected on the basis that it is inconvenient when applied in areas with different characteristics to those in the area in which the method was developed. In fact, in the study area, ICONA (1987) obtained values of 200 tm/ha/year of erosion applying the Universal Soil Loss Equation while Desir et al. (1992), in experimental plots, obtained rates of about 35 t/ha/year.

Both methodologies fulfil our main objective: the development of a map that can be introduced as a criterion map in subsequent land-use decision processes. For example, in the case of erosion susceptibility model, we sought to differentiate between weakly and highly susceptible areas, but not to quantify the amount of eroded material. This model, in addition to the agricultural capability of soils, was of great value for the land-use suitability analysis for the location of future irrigated agricultural land (see Lamelas, 2007; Lamelas et al., 2006a). Besides, the agricultural capability of soils was include in the land use suitability analysis for the location of new sand and gravel extraction sites as resources conservation is very import when a sustainable development it is going to be carried out (see Lamelas, 2007; Lamelas et al., 2007b).

In addition, our results match previous studies developed in the surrounding of the study area and most of it shows moderate general agricultural capability. The main limiting factor is the climate, due to the aridity of the study area. The degraded relief developed upon Tertiary gypsum, used for arable land, is also classified as moderately capable; however, in this case soil and climate are the limiting factors, reflecting the reduced useful thickness of the soil. The degraded relief developed upon Tertiary sediments with sclerophyllous vegetation is also classified as moderately capable, with slope being the limiting factor. Finally, endorheic areas are classified as having a marginal agricultural capability because of the salinity of the soils in such areas.

With respect to erosion susceptibility, degraded slopes developed in Tertiary sediments and used as irrigated land or covered by sclerophyllous vegetation have the highest susceptibility values, mainly due to poor texture, small useful soil depth, and steepness. Flat valley bottoms used for non-irrigated arable land or covered by sclerophyllous vegetation also have a high degree of erosion susceptibility, reflecting the poor soil characteristics, slope, and land cover in these areas.

In flat valley bottoms, the main erosion process is gully erosion, largely arising from the cessation of agricultural land use. Because of the static character of the employed land cover map, this process was not introduced in the model; consequently, the model may underestimate susceptibility values in areas with gully erosion. Nevertheless, this problem is a local phenomenon, and our results present susceptibility values at a regional scale using the homogeneous units as map units.

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8 Tables

Table 1: Reclassification of the geomorphology.

Lithology	Era	Period	Geomorphological description	Geomorphological homogeneous units
Red clays with centimeter levels of gypsum and limestones	Tertiary	Miocene Aragoniense	Slopes	Degraded relief
Tabular and nodular gypsum of massive aspect, with levels of shales	Tertiary	Miocene Aragoniense	Slopes	Degraded relief
Sandstones and red clays with levels of conglomerates	Tertiary	Miocene Aragoniense	Slopes	Degraded relief
Red clays and sandstnes	Tertiary	Miocene Aragoniense	Slopes	Degraded relief
Red clays and nodular gypsum	Tertiary	Miocene Aragoniense	Slopes	Degraded relief
Nodular gypsum, marls and ochre clays	Tertiary	Miocene Aragoniense	Slopes	Degraded relief
Gray marls and limestones	Tertiary	Miocene Aragoniense	Slopes	Degraded relief
Limestones and marls	Tertiary	Miocene Vallesiense	Estructural platform	Degraded relief
Clays and silts	Quaternary	Holocene	Endorheic area	Endorheic area
Pebbles, gypsiferous silts and clays	Quaternary	Holocene	Flat bottom valley	Flat bottom valley
Pebbles in silt-argilleous matrix	Quaternary	Early Pleistocene	Glacis 0	Glacis and alluvial fan
Pebbles in silt-argilleous matrix	Quaternary	Middle Pleistocene	Glacis I	Glacis and alluvial fan
Pebbles in silt-argilleous matrix	Quaternary	Upper Pleistocene	Glacis II	Glacis and alluvial fan
Pebbles in silt-argilleous matrix	Quaternary	Holocene	Glacis III	Glacis and alluvial fan
Gravels and pebbles in silt-agilleous matrix	Quaternary	Holocene	Actual glacis IV	Glacis and alluvial fan
Pebbles, sands and silts	Quaternary	Holocene	Alluvial fan	Glacis and alluvial fan
Gravels, sands, silts and clays	Quaternary	Early Pleistocene	Terrace (T7)	High terraces
Gravels, sands, silts and clays	Quaternary	Early Pleistocene	Terrace (T6)	High terraces
Gravels, sands, silts and clays	Quaternary	Middle Pleistocene	Terrace 70 m (T5)	High terraces
Gravels, sands, silts and clays	Quaternary	Upper Pleistocene	Terrace (T4B- Huerva)	High terraces
Gravels, sands, silts and clays	Quaternary	Upper Pleistocene	Terrace 30 m (T4)	High terraces
Gravels, sands, silts and clays	Quaternary	Upper Pleistocene	Terrace 20 m (T3)	High terraces
Gravels, sands, silts and clays	Quaternary	Holocene	Terrace 10 m (T2)	High terraces
Pebbles, clays and silts	Quaternary	Holocene	Flood plain 5 m (T1)	Low terraces
Gravels, sands and silts	Quaternary	Holocene	Present alluvial	Low terraces
River			River	River

Table 2: Reclassification of the Corine Land Cover map of 2004. Codige UE is the identification code assigned to the different land covers in the CORINE land use project.

Codige UE	Land cover description	Land cover homogeneous units
11100	Continuous urban fabric	Human infrastructure
11210	Discontinuous urban fabric	Human infrastructure
11220	Discontinuous urban fabric	Human infrastructure
12110	Industrial or commercial units	Human infrastructure
12120	Industrial or commercial units	Human infrastructure
12210	Road and rail networks and associated land	Human infrastructure
12220	Road and rail networks and associated land	Human infrastructure
12400	Airports	Human infrastructure
13100	Mineral extraction sites	Human infrastructure
13200	Dump sites	Human infrastructure
13300	Construction sites	Human infrastructure
14100	Green urban areas	Human infrastructure
14210	Sport and leisure facilities	Human infrastructure
14220	Sport and leisure facilities	Human infrastructure
21100	Non-irrigated arable land	Non-irrigated arable land
21210	Permanently irrigated land	Permanently irrigated land and forest
22223	Fruit trees and berry plantations	Non-irrigated arable land
22310	Olive groves	Non-irrigated arable land
22320	Olive groves	Non-irrigated arable land
24213	Complex cultivation	Permanently irrigated land and forest
24223	Complex cultivation	Permanently irrigated land and forest
24310	Agricultural land with areas of natural vegetation	Non-irrigated arable land
31120	Broad-leaved forest	Permanently irrigated land and forest
31130	Broad-leaved forest	Permanently irrigated land and forest
31150	Broad-leaved forest	Permanently irrigated land and forest
31210	Coniferous forest	Permanently irrigated land and forest
32122	Natural grassland	Sclerophyllous vegetation
32311	Sparcely vegetated areas	Sclerophyllous vegetation
32312	Sparcely vegetated areas	Sclerophyllous vegetation
32410	Transitional woodland shrub	Sclerophyllous vegetation
32420	Transitional woodland shrub	Sclerophyllous vegetation
33310	Sparcely vegetated areas	Sclerophyllous vegetation
41100	Inland marshes	Permanently irrigated land and forest
51110	Water courses	Water bodies
51220	Reservoir	Water bodies

Table 3: Assignment of soil types and capability classes in relation to site, soil, erosion risk and bioclimatic deficiency factor to the homogeneous units. S1, excellent; S2, good; S3, moderate; N marginal; t, site factor; l, soil factor; r, erosion risk factor; b, bioclimatic deficiency factor.

Landsacape homogeneous units	Site factor		Soil factor						Erosion risk factor				Bioclimatic deficiency factor	
	Slope %	Slope class	Morpho-edaphic units	Useful depth class	Texture class	Rockiness class	Drainage class	Salinity class	Soils erodibility class	Slope class	Vegetation density class	Rain erosivity class	Aridity	Frost risk
Flood plain with non-irrigated arable land and sclerophyllous vegetation	3.7	S1t	Calcaric Fluvisols	S1l	S1l	S1l	S1l	S1l	S1r	S1r	S2r	S1r	S3b	S2b
Flood plain with permanently irrigated land and forest	0.6	S1t							S1r	S1r	S1r	S1r	S3b	S2b
High terraces with non-irrigated arable land	3.0	S1t	Petric Calcisols	S2l	S1l	S2l	S1l	S1l	S2r	S1r	S2r	S1r	S3b	S2b
High terraces with permanently irrigated land	1.2	S1t							S2r	S1r	S1r	S1r	S3b	S2b
High terraces with sclerophyllous vegetation	9.6	S2t							S2r	S1r	S2r	S1r	S3b	S2b
Flat bottom valleys with non-irrigated arable land	8.1	S2t	Haplic Gypsisols	S1l	S1l	S1l	S2l	S1l	S1r	S1r	S2r	S1r	S3b	S2b
Flat bottom valleys with sclerophyllous vegetation	11.2	S2t							S1r	S1r	S2r	S1r	S3b	S2b
Glacis and alluvial fans with non-irrigated arable land	2.8	S1t	Calcaric Cambisols	S1l	S1l	S2l	S1l	S1l	S2r	S1r	S2r	S1r	S3b	S2b
Glacis and alluvial fans with permanently irrigated land	2.2	S1t							S2r	S1r	S1r	S1r	S3b	S2b
Degraded slopes in Tertiary materials with sclerophyllous vegetation	18.8	S3t	Calcaric Regosols	S3l	S1l	S1l	S11l	S1l	S2r	S2r	S2r	S1r	S3b	S2b
Degraded slopes in Tertiary materials with non-irrigated arable land	10.4	S2t							S2r	S1r	S2r	S1r	S3b	S2b
Endorheic areas with permanently irrigated land	0.7	S1t	Haplic Solonchaks	S1l	S2l	S1l	S3l	Nl	S1r	S1r	S1r	S1r	S3b	S2b
Water bodies	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data
Human infrastructures	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data

Table 4: Matrix of degrees employed for the site factor.

Capability class	Description	Slope type	Slope %
S1t	Excellent	Null or smooth	< 7
S2t	Good	Moderate	7-15
S3t	Moderate	Strong	15-30
Nt	Marginal	Steep	> 30

Table 5: Matrix of degrees employed for the erosion risk factor.

Capability class	Description	Soils erodibility	Slope %	Vegetation density %	Rain erosivity
S1r	Excellent	Low	< 15	High >30%	< 250
S2r	Good	Moderate	15-30	Moderate 15-30 %	250-300
S3r	Moderate	High	> 30	Null <15%	300-375
Nr	Marginal	-	-	-	>375

Table 6: Slope steepness classes. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Slope steepness %	Description	Rating
0-3	Flat or almost flat	1
3-8	Gently sloping	2
8-14	Sloping	4
14-21	Moderately steep	8
21-56	Steep	16
56-140	Very steep	24
> 140	Extremely steep	32

Table 7: Slope length classes. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Slope length (m)	Description	Rating
< 15	Very short	1
15-50	Short	2
50-150	Moderately long	4
150-300	Long	6
> 300	Very long	8

Table 8: Ratings of slope, land cover, erosion, soil and conservation practices factors, total score and erosion susceptibility class for the different homogeneous units.

Landsacape homogeneous units	Slope factor			Land cover factor	Erosion factor				Soils factor				Conservation practices		Total score	Erosion class
	Slope steep-ness	Slope length	Slope shape		Wind erosion	Sheet erosion	Rill-gully erosion	Mass move-ment	Useful depth	Texture	Sealing suscepti-bility	Consoli-dation	In plain	In drainage ways		
Flood plain with non-irrigated arable land and sclerophyllous vegetation	2	4	3	4	1	1	0	0	1	1	3	4	0	0	28	moderate
Flood plain with permanently irrigated land and forest	1	4	3	1	1	1	0	0	1	1	3	4	-4	-2	18	weak
High terraces with non-irrigated arable land	2	4	3	8	2	2	0	0	2	1	2	2	0	0	32	moderate
High terraces with permanently irrigated land	1	4	3	1	1	1	0	0	2	1	2	2	-4	-2	16	weak
High terraces with sclerophyllous vegetation	4	4	3	4	2	2	0	0	2	1	2	2	0	0	30	moderate
Flat bottom valleys with non-irrigated arable land	4	4	3	8	1	2	2	1	1	8	3	4	-4	0	41	high
Flat bottom valleys with sclerophyllous vegetation	4	4	3	4	1	1	2	1	1	8	3	4	0	0	40	high
Glacis and alluvial fans with non-irrigated arable land	2	4	2	8	2	2	1	0	1	1	3	4	0	0	34	moderate
Glacis and alluvial fans with permanently irrigated land	1	4	2	1	1	1	1	0	1	1	3	4	-4	-2	18	weak
Degraded slopes in Tertiary materials with sclerophyllous vegetation	8	4	3	4	2	4	4	2	3	8	3	4	0	0	57	very-high
Degraded slopes in Tertiary materials with non-irrigated arable land	4	4	3	8	2	4	4	2	3	8	3	4	0	0	57	very-high
Endorheic areas with permanently irrigated land	1	4	1	1	1	1	0	0	1	4	3	4	-4	-2	19	weak
Water bodies	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data
Human infrastructures	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data	No-data

Table 9: Vegetation density and land cover condition classes. Source: slightly modified according to van Zuidam and van Zuidam-Cancelado (1979).

Vegetation density %	Land use condition	Rating
> 75	Very dense crops, permanent grass or dense shrub and woodland/forest	1
50-75	Dense/ degraded woodland	2
25-50	Moderate/tree and other perennial crops; grazing land	4
10-25	Sparse distributed crops/ cut over or bunt over forest area	8
> 10	Barren/fallow land	16

Table 10: Wind, sheet, rill-gully erosion and mass movement hazard classes and ratings. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Class	Rating
None	0
Slight	1
Moderate	2
Severe	4

Table 11: Useful depth factor classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Useful depth (cm)	Description	Rating
> 150	Very deep	1
100-150	Deep	1
50-100	Moderately deep	2
25-50	Shallow	3
<25	Very shallow	4

Table 12: Texture factor classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Texture	Rating
Peaty	1
Gravelly	1
Coarse sandy	2
Silty and clayey	4
Fine sandy and silty	8

Table 13: Sealing susceptibility classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Sealing susceptibility	Rating
None	0
Slight	2
Moderate	3
Severe	5

Table 14: Structure of underlying strata classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Strata structure	Rating
Horizontally bedded	0
Vertically bedded	1
Sloping bedded/face slope	1
Sloping bedded/traverse slope	2
Sloping bedded/dipslope	3

Table 15: Depth of impermeable layer below surface classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Impermeable layers depth (cm)	Description	Rating
> 150	Deep	0
100-150	Moderately deep	1
50-100	Moderately/shallow	2
< 50	Shallow	4

Table 16: Classes and rating for conservation practices in plain. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Conservation practices in plain	Rating
Bench terracing	-6
Contour terracing with strip cropping	-4
Contour ploughing/strip cropping	-2

Table 17: Classes and rating for conservation practices in drainage ways. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Conservation practices in drainage ways	Rating
Check dams (silt trap dams; gully head dams; drop structures, gabions)	-4
Lined river channel constructions	-2
Others	-1

9 Figures

Figure 1: Location maps of the study area.

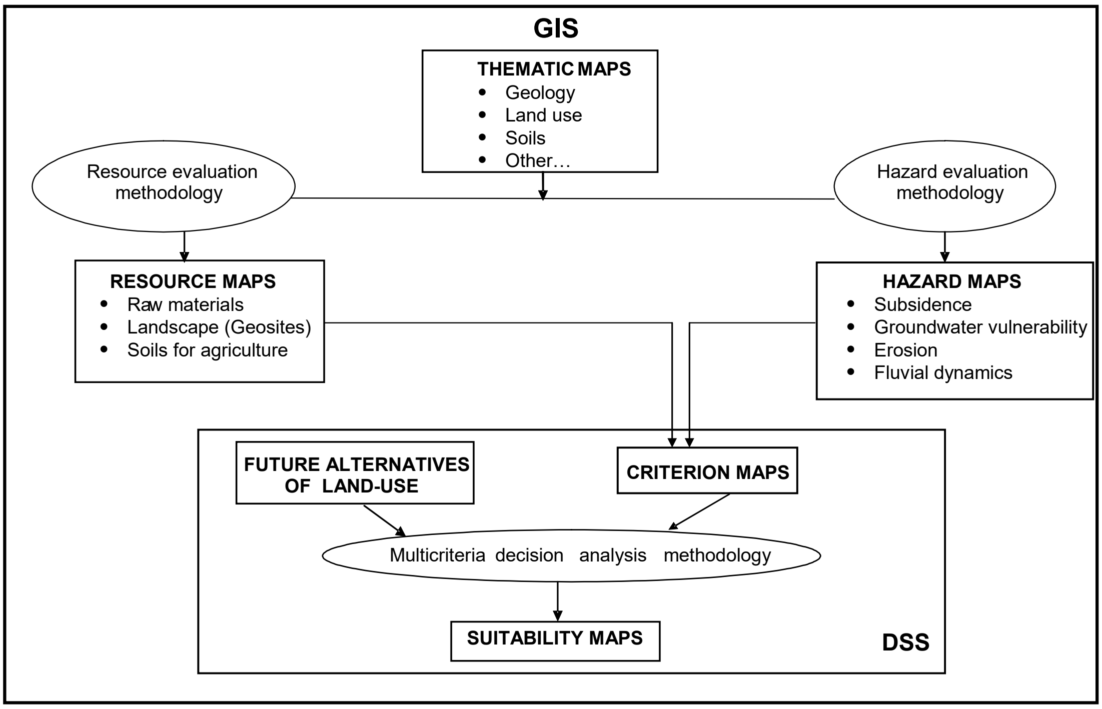

Figure 2: Conceptual scheme for land-use decisions (spatial decision support system comprising the integration of decision support systems (DSSs) into a geographic information system (GIS)).

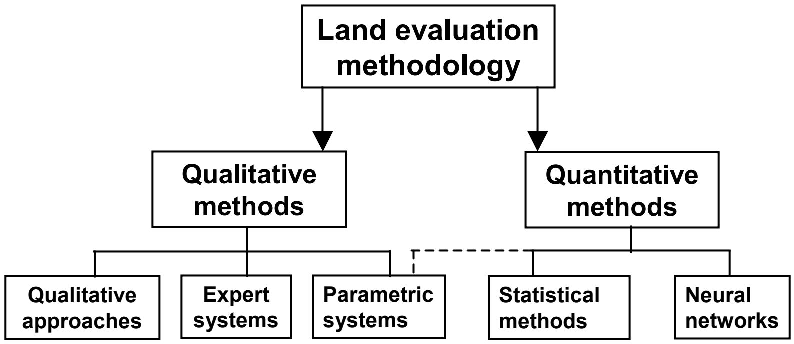

Figure 3: Land evaluation methodologies.

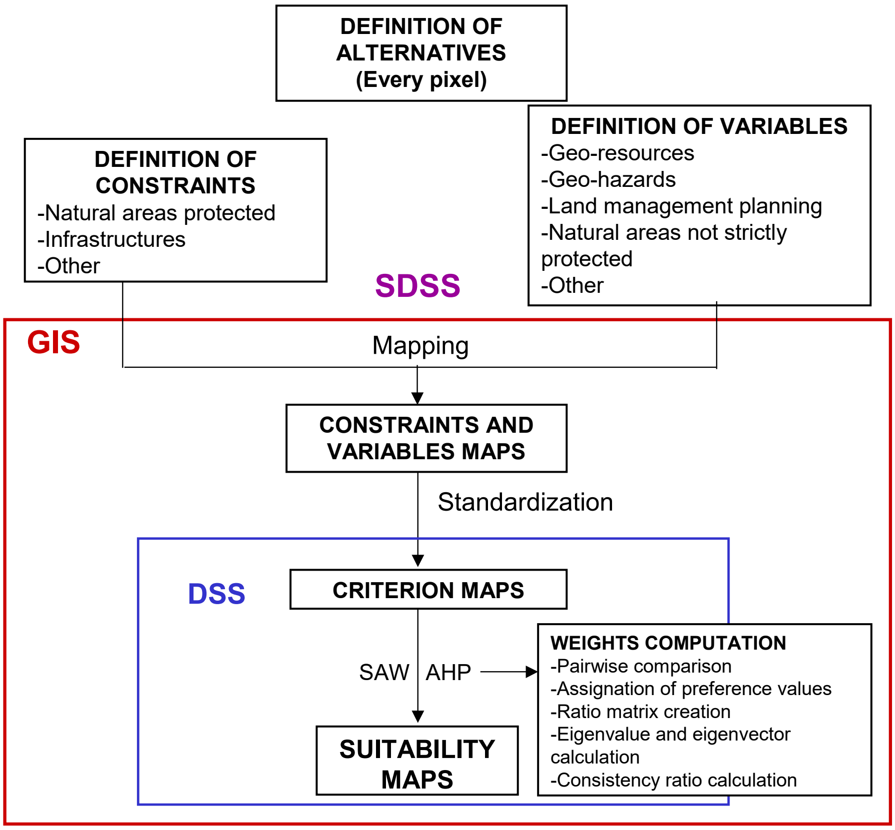

Figure 4: Scheme employed for site search analysis. Source: Lamelas et al. (2006a).

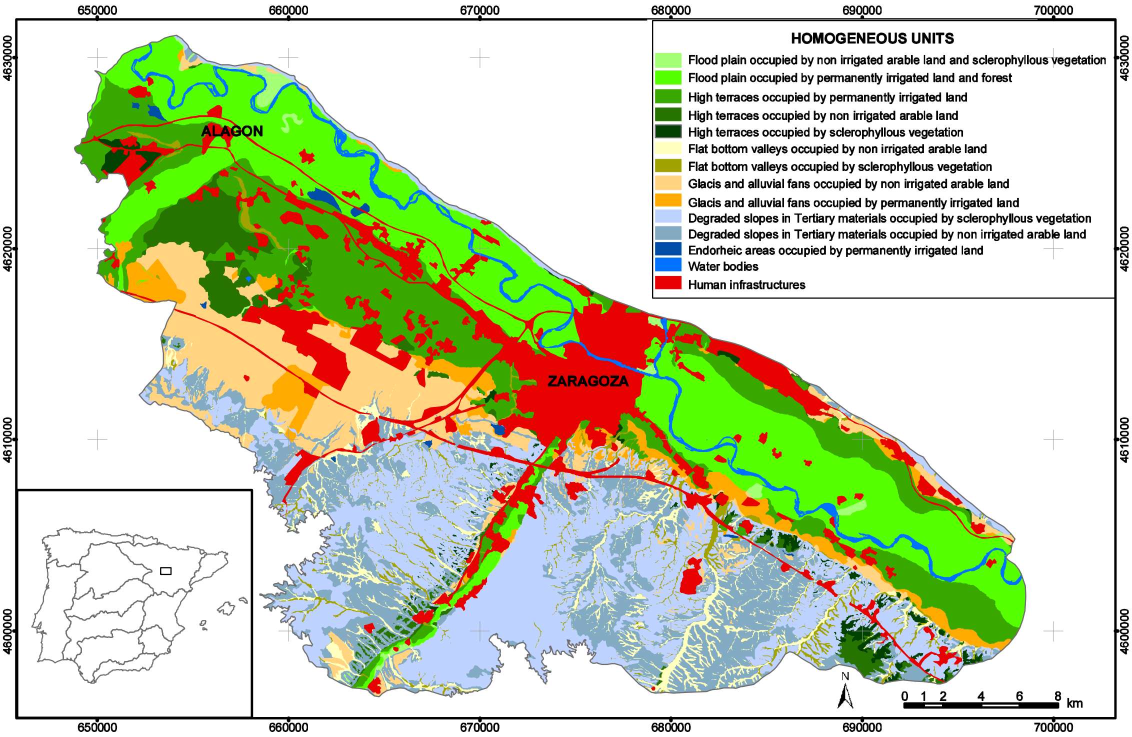

Figure 5: Map of the determined homogeneous units.

Figure 6: Map of the determined morphoedaphic units

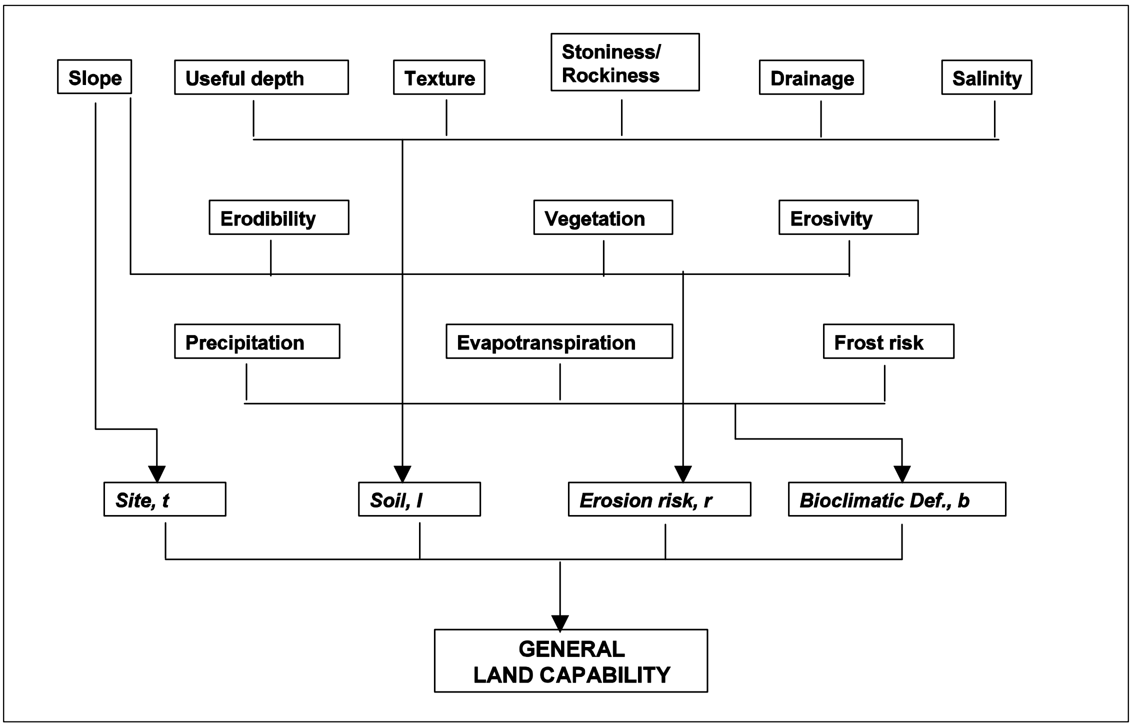

Figure 7: Factors employed in the general land capability (source: CSIC, 2004).

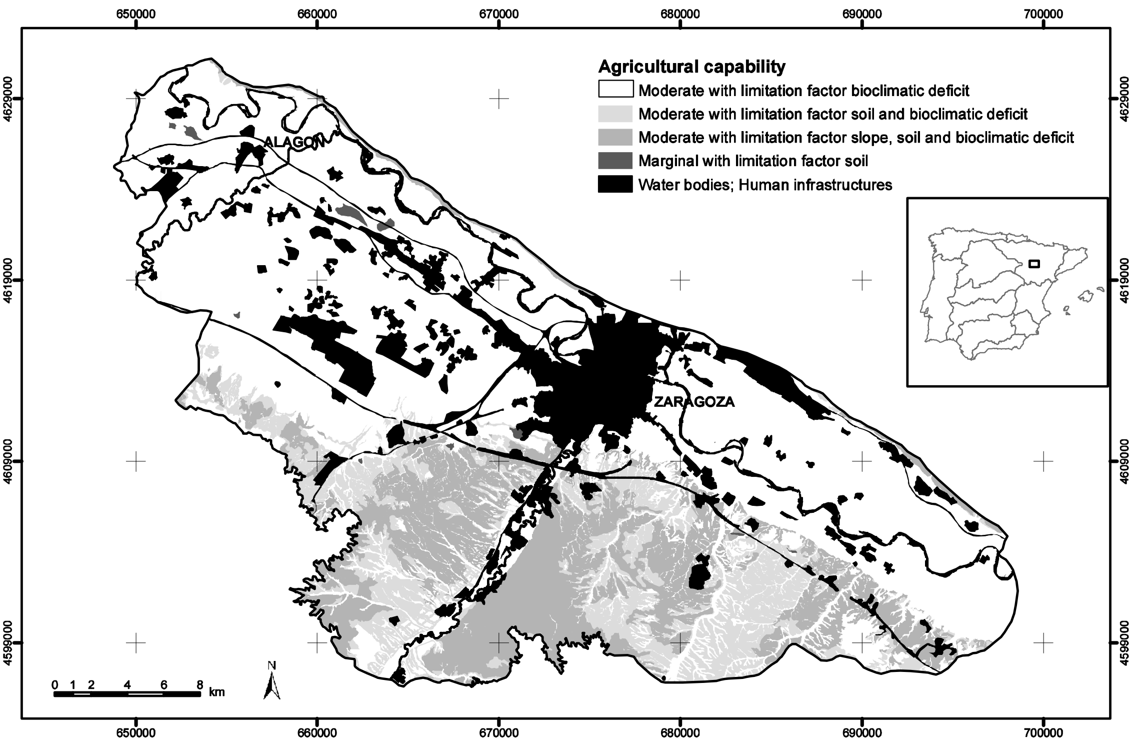

Figure 8: Map of the determined general agricultural capability.

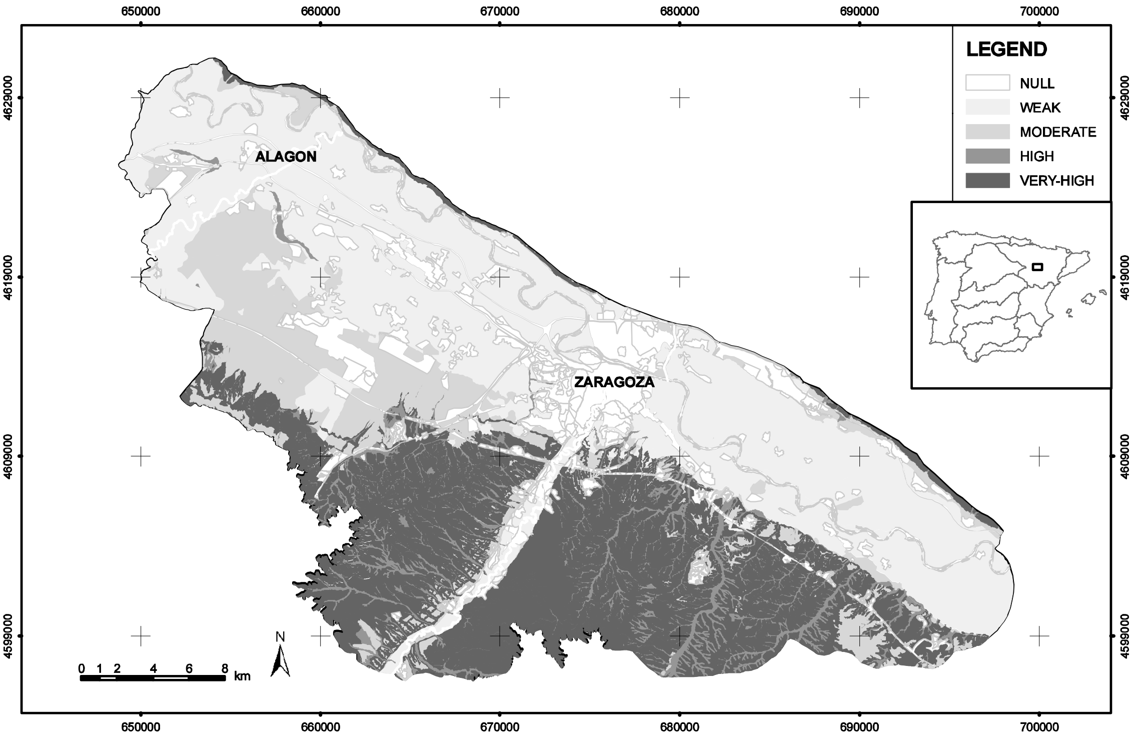

Figure 9: Map of the determined erosion hazard.