Geo-resources and geo-hazards in the context of a sustainable development in the periphery of urban areas, exemplary of a part of the Ebro Basin in the surroundings of Zaragoza (Spain)

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KURZFASSUNG

Obwohl Nachhaltigkeit ein häufiges Schlagwort in Debatten um die Zukunft der Gesellschaft und ihrer Bedürfnisse ist (z.B. Agenda 21), sind viele Fragen zu einer nachhaltigen Entwicklung des Ebro-Beckens in der Umgebung von Zaragoza offen.

Zaragoza liegt im zentralen Teil des Ebro-Beckens, und gehört mit seinen knapp 700.000 Einwohnern zu den wirtschaftlich wichtigen und dynamisch wachsenden Gebieten der Iberischen Halbinsel. Der Untergrund dieser Region wird von gipsreichen Playa-Sedimenten des Oligozän und Miozän gebildet, die nur in einigen Teilgebieten von Pedimenten und Terrassen des Ebro und seiner Nebenflüsse bedeckt sind.

Während der schnellen Wirtschafts- und Stadtentwicklung wurde der Einfluss der Geosphäre im Umfeld von Zaragoza wenig beachtet. Die Folgen waren unter anderem die Zerstörung der Infrastruktur durch Hangrutschungen, Verluste an wertvollen landwirtschaftlichen Nutzflächen und Naturräumen sowie wachsende Beeinträchtigungen der Grundwasserqualität.

Um sicherzustellen, dass Landnutzungsentscheidungen in hohem Maße nachhaltig sind, müssen andererseits gerade standortgebundene Geo-Ressourcen und Geo-Risiken berücksichtigt werden. Sie wurden daher mit Hilfe eines Geographischen Informationssystems (GIS) regionalisiert.

In einem ersten Schritt wurden alle verfügbaren geowissenschaftlichen Daten gesammelt, analysiert und für die Einbindung in ein Geographisches Informationssystem aufbereitet, um sie in Karten darzustellen (Geologie, Geomorphologie, Böden, Klima, Vegetation, Landnutzung, Naturschutzgebiete).

Anschließend wurden Geo-Risiken (Erosion, Gefährdung durch Erdfälle und Grundwasserverschmutzungsempfindlichkeit) und Geo-Ressourcen (Sand- und Kies-Lagerstätten, Eignung der Böden für die Landwirtschaft) mit Hilfe eines Geographischen Informationssystems und 3D-Verfahren ermittelt, beschrieben und modelliert. Die Wahl der Landbewertungsmethodiken für die Modellierung von Geo-Risiken und Geo-Ressourcen erfolgte unter Berücksichtigung der Verfügbarkeit und Qualität der Information für ihre Entwicklung, ihrer Eignung für das Arbeitsgebiet und des Zwecks der Modelle.

Der dritte Schritt hatte das Ziel der „Entwicklung einer GIS-gestützten Gefährdungsabschätzungs- und Entscheidungsmethodik für nachhaltige Land- und Ressourcennutzungsentscheidungen“ (so der Titel des von der Deutschen Forschungsgemeinschaft geförderten Projekts). Hier wurden die im GIS gespeicherten Karten mit multikriteriellen Bewertungsmethoden verknüpft, um Eignungskarten für verschiedene Landnutzungsformen zu entwickeln (Flächen für Sand- und Kiesabbau, Bewässerungsland, industrielle und städtische Nutzung). Bei konkurrierenden Nutzungsinteressen lassen sich damit nach einer Priorisierung der verschiedenen Nutzungen für eine bestimmte Nutzungsform geeignete bzw. weniger oder nicht geeignete Gebiete diskretisieren.

Besonderes Augenmerk wurde dabei auf den Schutz des Grundwassers vor Verschmutzung und die Gefährdung durch Erdfälle gelegt. Außerdem wurde die weitere Verfügbarkeit der Massenrohstoffe Sand- und Kies untersucht, wobei sich die Entwicklung eines dreidimensionalen geologischen Modells als besonders hilfreich erwies.

Die Regionalisierung der beschriebenen Geo-Potenziale, ihre Übersetzung in Thematische Karten und die Priorisierung mit den Werkzeugen multikriterieller Bewertungsmethoden sind damit ein wichtiger Schritt zu einer nachhaltigen Entwicklung, auch im Sinne der Agenda 21.

ABSTRACT

Although sustainability is a term frequently used in debates on the future of society and its needs (e.g. Agenda 21), many questions seemed to be open with respect to a sustainable management of the Ebro Basin in the surrounding of Zaragoza.

This city of about 700.000 inhabitants is located in the central part of the Ebro Basin. This is a highly dynamic economic axis and densely populated area within the Iberian Peninsula. In this sector, the Tertiary playa-lake deposits of Oligocene to Miocene age are only covered, in some areas, by pediments and terraces of the Ebro River and its tributaries.

In the periphery of Zaragoza, the interactions with the geosphere have been largely ignored due to the fast economic and urban development of this city. This resulted among others in the destruction of many infrastructures caused by land subsidence, a loss of valuable agricultural land and valuable natural areas and an increasing aquifer contamination.

At present, to ensure that land-use decisions imply a high degree of sustainability, it must be taken care of geo-resources and geo-hazards. Therefore, they were regionalised using Geographical Information Systems.

In a first step, all available geoscientific data was collected, analysed and prepared for its introduction into a Geographical Information System in order to be mapped (geology, geomorphology, soils, climate, vegetation, land-use, natural protected areas).

Afterwards, geo-hazards (erosion, dolines susceptibility and groundwater vulnerability) and geo-resources (sand and gravel deposits, agricultural capability of soils) were detected, described and modelled with the help of Geographical Information System and 3D techniques. The selection of the land evaluation methodologies for geo-hazards and geo-resources modelling was made considering the availability and quality of information for their development, their suitability to the study area and the final objective of the models.

The third step aims to develop a GIS-based risk-assessment and decision methodology for sustainable land and resource use decisions (as the title of the project promoted by the German Research Foundation). Here the maps stored in the GIS were combined with multi-criteria evaluation methodologies in order to develop different land-use suitability maps (sand and gravel extraction sites, irrigated land, industrial and urban use).

After assigning priorities to individual land uses in case of competing land use interests, areas that are suitable, minor suitable or unsuitable for a special type of land use can be identified.

Special attention within this process was put on the groundwater protection and the dolines susceptibility. Moreover the availability of raw materials as sand and gravel was examined. Here the development of a three-dimensional geological model proved to be especially helpful.

The regionalisation of the described geo-potentials, their translation into thematic maps and their prioritising using multi-criteria evaluation methods are thereby an important step to a sustainable development, also in the sense of the Agenda 21.

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1. Introduction

Zaragoza city is located in the central part of the Ebro Basin, within the Aragon Region, in the north-east of the Iberian Peninsula (Figure 1). The triangularly shaped Ebro Basin is limited in the north by the Pyrenees, in the south-west by the Iberian Range and in the south-east by the Catalan Coastal Range.

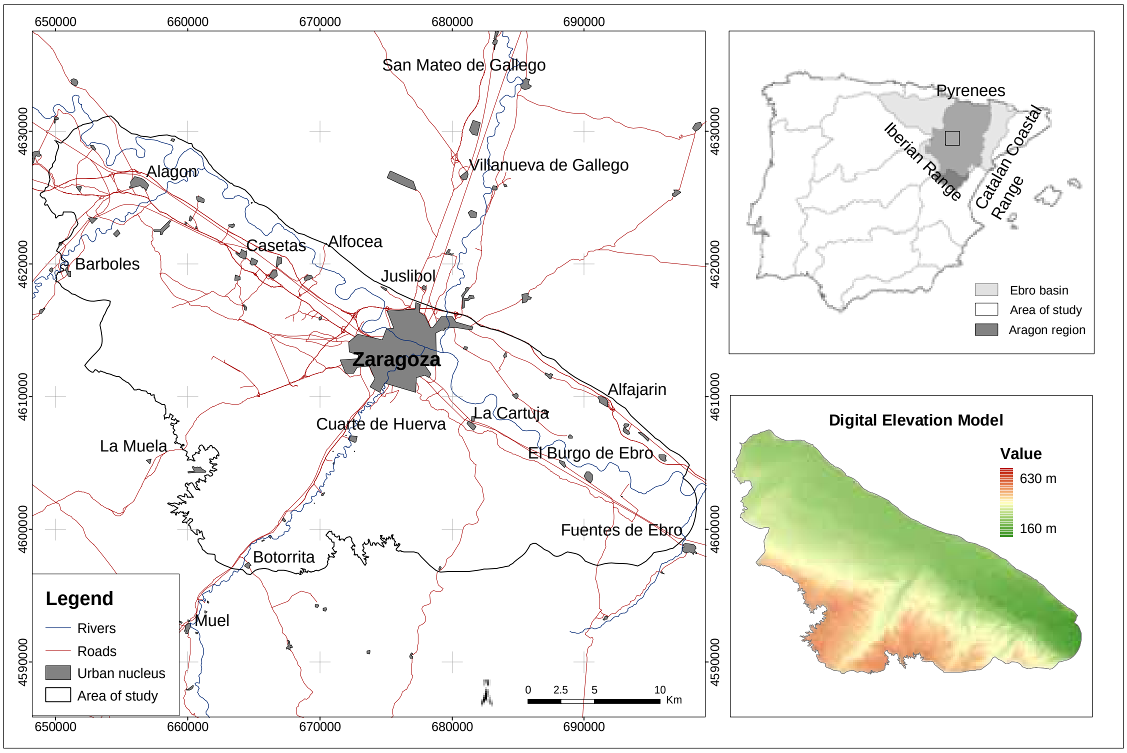


Figure 1: Location of the study area.

The Tertiary continental sedimentary infill of the basin is composed of conglomerates and sandstones at the margins, grading into clays, marls, evaporites and carbonate facies towards the depocentre of the basin (Benito *et al*., 1998). In the central part of the basin, the playa-lake deposits form the greatest gypsum outcrop of the area, only covered, in some areas, by the different pediments and terraces deposited during the Quaternary by the Ebro River and its tributaries (see chapter 3.1.2.).

The climate in this area has semi-arid characteristics, with mean annual precipitation of about 350 mm and mean annual temperature of about 15º C. The Continental Mediterranean Climate of Zaragoza is also characterized by its irregular distribution of precipitation (see chapter 3.1.1. and Figure 10).

This city is located inside the homonym area in the region *Corredor del Ebro* (Ebro Corridor), a highly dynamic economic axis and densely populated area within the Iberian Peninsula. Under these conditions of highly anthropogenic impact and semi-arid climate, the scarce natural vegetation that still remains corresponds to sclerophyllous scrub, gypsum steppes and riparian forest and thickets (see chapter 3.1.5).

In the national Ley del Suelo in 1956 (Land-use Law), the first regulation of land use in Spain, anticipated an increase in population of up to 500,000 inhabitants by the year 2000. However, its strategic position in the middle of four of the most important developed areas inside the Iberian Peninsula (Madrid, Barcelona, País Vasco and Valencia), and the declaration of the city, in 1964, as Focus of Industrial Development (Polo de Desarrollo Industrial) brought about a very high increase in population, which rose to 500,000 inhabitants by the 70s (see chapter 3.2.). Today, the city has a total population of about 700,000 (more than 60% of the total population in Aragon Region) and it is expected to increase even more in the next decade due to the demand of workers by the city in order to organize the 2008 EXPO under the title “Water and Sustainable Development”. This increase in population was accompanied by a great urban development. Thus, nowadays, the city covers more than twice the area occupied by Zaragoza at the beginning of the 20th century (Figure 2).

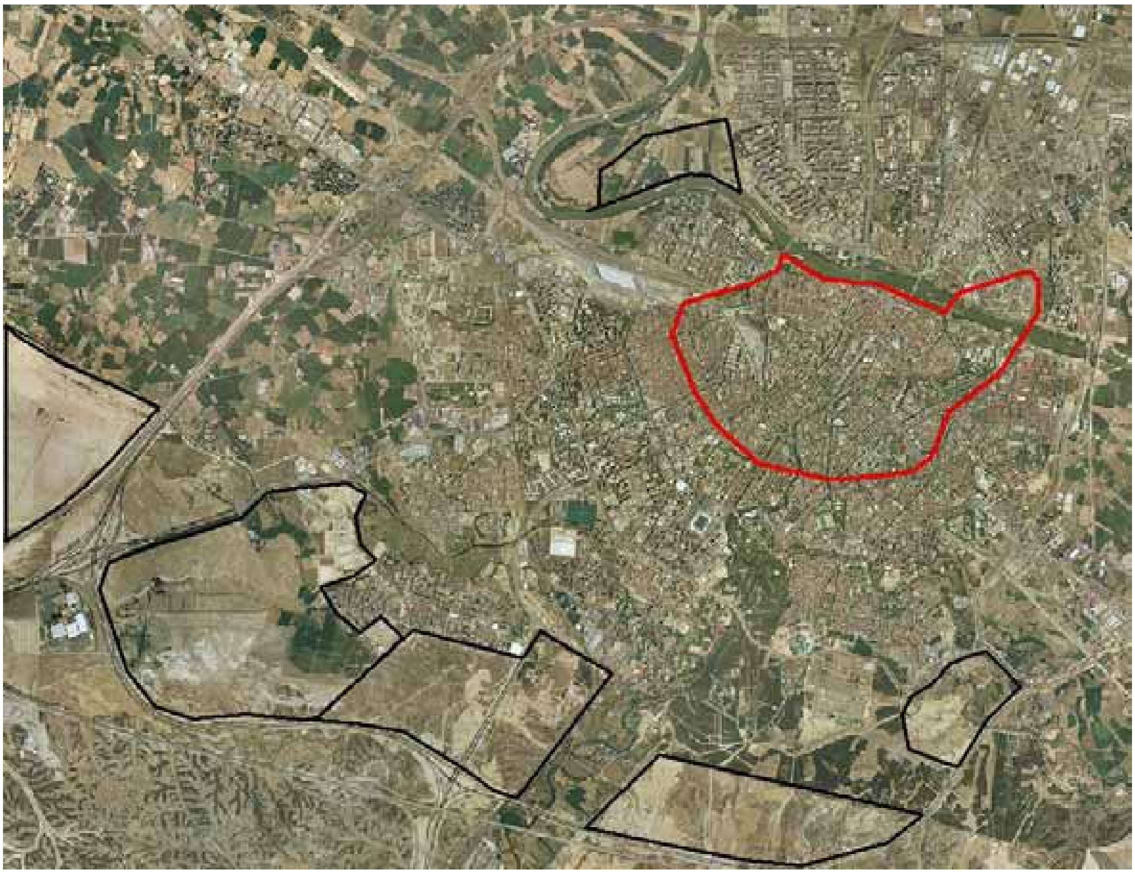


Figure 2: Ortoimage from Zaragoza, 2004. Source: Zaragoza Council. In red colour is delineated the approximate extension of Zaragoza in 1927. The areas under construction, at present, are shown in black.

And this is precisely one of the principal challenges for the 21st century: supporting the sustainable development of large cities. Nevertheless, the relationship between economic development and environmental sustainability is complex. For instance, in the periphery of Zaragoza, due to the fast urban development, interactions with the geosphere have been largely ignored. This resulted among others in the destruction of many infrastructures caused by land subsidence, a misuse of valuable agricultural land, the destruction of several valuable natural areas and an increasing aquifer contamination.

Before the Rio declaration of the United Nations in 1992 (**http://www.un.org**), Agenda 21 and its further implementation program, most literature on sustainable development did not mention cities. This reluctance to discuss sustainable development and cities probably reflects the disdain with which many of those who write on environmental issues have long regarded cities , even if they live in them. The outcome is a rather poorly developed literature on sustainable development and cities in the seventies and eighties (McGranahan and Satterthwaite, 2003; Mitlin and Satterthwaite, 1996).

After the Rio Declaration, which reaffirmed the Declaration of the United Nations Conference on the Human Environment adopted at Stockholm on 16 June 1972, the promotion of a sustainable human settlement development have been a serious concern. In the 1990’s, several international conferences were organised in order to address the issues of rapid urbanisation, development and management, and the term Megacity was widely spread. In fact, Agenda 21 suggests that each local authority should enter into a dialogue with its citizens, local organizations and private enterprises and adopt "a local Agenda 21" for their own community.

The World Commission on Environment and Development (WCED, 1987) defined sustainable development as “development that meets the needs of present generations without compromising the ability of future generations to meet their own needs” (cited by Pugh, 1996; Gilpin, 2000; McGranahan and Satterthwaite, 2003).

Later approaches, *i.e.* Munasinghe (1993) and Munasinghe and Cruz (1995), distinguish “economic”, “social” and “environmental“ sustainability (Figure 3). Thus, economic sustainability is understood as generating a maximum flow of economic welfare whilst maintaining the stock of assets, including environmental assets; social sustainability is people-oriented, identified with the stability and cultural diversity of social systems; and environmental sustainability refers to the preservation, the resilience and the adaptation of physical and biological systems (Pugh, 1996; Gilpin, 2000). A good definition of what implies sustainable development in urban centers can be found in McGranahan and Satterthwaite (2003). It includes, in addition to economic, environmental and social nedds, political needs which includes freedom to participate in national and local politics and in decisions regarding management and development.

The fifth principle of Agenda 21 (**http://www.un.org/esa/sustdev/**) suggests that all states and all people shall cooperate in the essential task of eradicating poverty as an indispensable requirement for sustainable development, in order to decrease the disparities in standards of living and better meet the needs of the majority of the people of the world. This implies not only an intergenerational sustainable development, but also an intragenerational sustainable development. In agreement with Gilpin (2000), this is a major concern, as nowadays the problems of intergenerational equity (Fairness within Today´s Society) are much more readily addressed than the problems of intragenerational equity (Fairness between Generations).

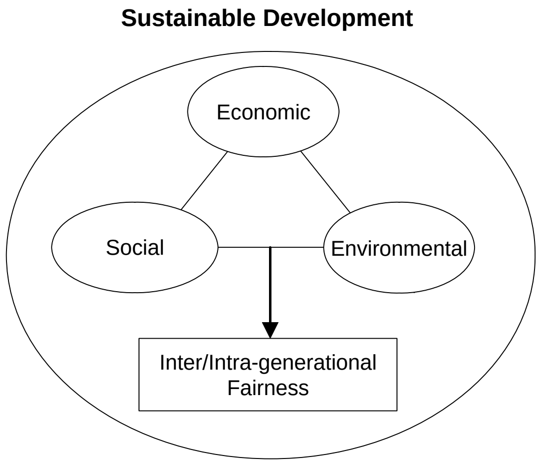


Figure 3: Components of sustainable development.

According to Agenda 21 (**http://www.un.org/esa/sustdev/**), in rapidly growing urban areas, access to land is rendered increasingly difficult by the conflicting demands of industry, housing, commerce, agriculture, land tenure structures and the need for open spaces.

Besides, in many countries, the use of land in large urban areas is a serious problem, especially as resources which are vital for these fast growing settlements are sealed away. Among these resources are groundwater, valuable soils for agriculture and mineral deposits including raw materials (sand, gravel, limestone). As a result, it is difficult to access clean drinking water in many areas and large amounts of construction material have to be transported over long distances (Hoppe *et al.*, 2006a).

Dense population also increases the possibilities that natural hazards (earthquakes and tsunamis, mass transports on steep slopes or by subrosion of evaporites in the underground as well as volcanism) may turn into risks and eventually may lead to catastrophes (Hoppe, 2002; Hoppe *et al.*, 2006a; Plate and Merz, 2001; Wellmer and Becker-Platen, 1999, 2002).

According to Agenda 21 (**http://www.un.org/esa/sustdev/**), over the past two decades, natural disasters are estimated to have caused some 3 million deaths and affected 800 million people. Global economic losses have been estimated by the Office of the United Nations Disaster Relief Coordinator to be in the range of $30-50 billion per year. However, the Munich Re Group Annual Review on Natural Catastrophes in 2005 (**http://www.munich-re.com**) states that, as in previous years, the number of events in 2005 was dominated by weather-related natural catastrophes.

More research on natural disasters is being carried out today than ever before. This may be due to the increasing global disaster toll, the disproportionately high burden of losses in poor countries and the framework of specific research objectives defined by the United Nations, who designated the 1990s the International Decade for Natural Disaster Reduction (IDNDR) (Chester, 2002; Degg, 1998; Mamud and Eddleston, 1998). In addition, this designation has produced several conferences and workshops in which specialists from many diverse fields (physical scientists, social scientists, engineering, insurers, environmentalists, development agencies and politicians) have met (Degg, 1998).

Agenda 21 (**http://www.un.org/esa/sustdev/**) suggests that: "all countries should consider appropriate undertaking national inventory of their land resources, in order to establish a land information system in which land resources will be classified according to their most appropriate uses, and environmentally fragile or disaster-prone areas will be identified for special protection measures. The overall objective is to improve or restructure the decision-making process, so that consideration of socio-economic and environmental issues may be fully integrated and a wider range of public participation assured".

However, although land-use decisions are usually made on the basis of a variety of criteria (economical, ecological and social), geoscientific aspects are very rarely considered or they are regarded as criteria of less importance (Hoppe *et al*., 2006a; Marker, 1998). Nevertheless, areas containing geo-resources, or posing geo-hazards, cannot be modified by man. They usually have longer cycles of regeneration than human lifetimes and may affect the interests of several generations. As a consequence, all land-use planning -especially in growing communities- should take a close look into the geo-potentials, which means all relevant geo-resources and geo–hazards (Hoppe *et al.*, 2006a).

In order to fulfil land management functions, the tools to be used must be updatable, multiscalar and should contain a wide rage of information concerning the environment, *i.e.* the physical, biotic and anthropic aspects and their interrelations. From this point of view, a Geographical Information System is needed (Amadio *et al.*, 2002).

Environmental management was a prime motivator for the development of Geographical Information Systems, and a major area of application, throughout its history. The first Geographical Information System, the Canada Geographic Information System, was developed in the mid 1960s in order to provide the Government of Canada with information about the utilization and management of Canada´s land resources (Goodchild, 2003). In addition, new technologies, in particular remote sensing and Geographical Information Systems, have had a major impact on hazard studies (Chester, 2002).

Besides, in the last years, the development of Spatial Decision Support Systems has proved a considerable aid in the efforts for solving land-use conflicts that commonly appear in sustainable land-use management schemes. These systems combine the benefits of Geographical Information Systems and decision support methodologies, and are therefore suitable to support the sustainable development of urban areas by means of land-use suitability analysis.

According to all these facts, the surroundings of Zaragoza city, a large and growing urban nucleus, need closer investigation with regards to geoscientific aspects in order to regionalise its geo-resources and –as far as possible- its geo-hazards. This information will be introduced to a Geographical Information System with integrated decision support tools in terms of multi-criteria evaluation methodologies (Spatial Decision Support System), which may help spatial managers to optimise land-use planning.

2. Objectives, hypotheses and methodology

2.1. Objectives

The main objective of this study is the development of a methodology, which will facilitate the geo-hazards and geo-resources 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 is 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 Geographical Information System environment.
- Geo-hazards and geo-resources detection, description and modelling with the help of Geographical Information System 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:
    i. Geo-hazards: doline and erosion susceptibility, groundwater vulnerability, floods.
    ii. Geo-resources: raw materials (sand and gravels), soils for irrigated agricultural use.
    iii. Other resources: natural areas, valuable from the environmental and geoscientific point of view,
- Land-use (sand and gravel extraction, irrigated land, industrial areas and urbanization) suitability analysis by means of Spatial Decision Support Systems:
    i. Site search analysis: location of best areas for a particular land-use system.
    ii. Site selection analysis: ranking of existing alternatives for different land-use forms.

2.2. Hypotheses.

The development of new technologies and especially Geographical Information System and its application to land evaluation modelling will make it possible to develop accurate geo-hazard and geo-resource mapping for the Zaragoza periphery on a regional scale. The introduction of three-dimensional information in the modelling process will improve even more the quality of the results according to the natural three-dimensional characteristic of some of the subsystems of the environment such as geology and hydrogeology. Moreover, the application of Spatial Decision Support Systems will allow us to perform subsequent land-use suitability analysis, which will help in the proper location of diverse land use systems with regards to geoscientific aspects. Thus, the methodology developed during this project and the results of this research would very likely serve to support the land-use management and the sustainable development of growing cities, in particular the surroundings of Zaragoza.

2.3. Methodology

2.3.1. Project workflow

Figure 4 shows the project workflow. The first step involves the gathering of as much information as possible about geology, geomorphology, soils, vegetation, land use, etc. This information will be introduced in a Geographical Information System. Then, the land will be evaluated with respect to its geo-hazards and geo-resources, developing different models with the help of different hazard and resource evaluation methodologies. In some cases, the development of these methodologies will imply the use of interpolation methods for the regionalisation of some characteristics of the environment. Afterwards, all these models will be introduced as criteria in a Decision Support System (DSS) integrated in a Geographical Information System, what is called a Spatial Decision Support System, which will allow us to develop several suitability maps for different land-use forms.

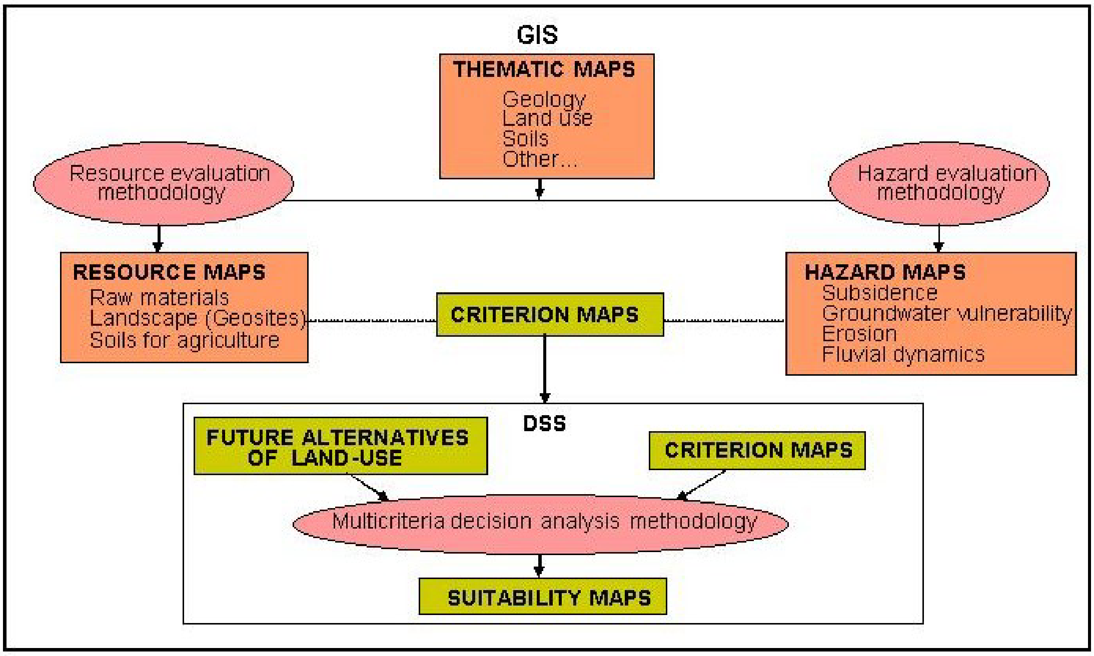


Figure 4: Conceptual scheme for land-use decisions (Spatial Decision Support System as the integration of DSS, Decision Support Systems, into Geographical Information Systems).

2.3.2. Data collection

The first stage is the collection of information related to geological, geomorphological and hydrogeological characteristics, land cover, soil properties, climate, infrastructures, protected and worth protecting areas, etc. and its integration into a Geographical Information System database, in this case ArcGIS 9.1 (ESRI, 2005). Data gathering must depend on the objectives of the study. These objectives may change with time, determining the dynamic character of the data collection. At this stage a good conceptualisation of the Geographical Information System database becomes fairly important. Compilation of information (Figure 5) includes:

- Searching of the best information available.
- Analysing its characteristics.
- Introduction of the information to a Geographical Information System which implies correct georeferenciation and, in some cases, format conversion, for instance.
- Creation of new digital information by digitalising analog maps or analysing air photographs.

A parallel phase is the gathering of methodologies for the land evaluation modelling: development of hazard models (sinkhole development, groundwater vulnerability, erosion), and resource cartography (soils for agriculture, raw materials, landscapes).

Geology, geological 3D model (Gocad):
- Geological map 1:50,000, ITGE (National Geological Institute). Format ArcGis
- Information boreholes in IPA (Inventory of water points) from C.H.E. (Ebro Basin Authority)
- Information sounding enterprises and MOPU (Ministery of Public Works)

Subsidence hazard map:
- Geological map 1:50,000, ITGE. Format ArcGis
- Geological model
- Hydrochemical information and water table in IPA (Water Points Inventory, Ebro Basin Authority)
- Cartography of dolines in previous studies and air photography analysis
- Cartography of irrigation areas and canals with amount of water (Ebro Basin Authority)

Ground water vulnerability:
- Geological map 1:50,000, ITGE. Format ArcGis
- Geological model
- Water table in IPA
- Cartography and database with information about soils
- Meteorological data (INM, National Meteorological Institute)
- Irrigation data

Fluvial hazards:
- Cartography of periods of return of flood (Ollero, 1996)

Erosion hazard:
- Cartography of morphoedaphic units
- Data about analysis of soils
- Meteorological data
- DEM (Digital Elevation Model) pixel side 20 m (Ministry of Agriculture)
- Cartography of CORINE Land cover 1:100,000 (2000)
- Geological map 1:50,000, ITGE. Format ArcGis
- Airphotographs
- Expert knowledge

Agricultural capability of the soil:
- Cartography of morphoedaphic units.
- Data about analysis of soils
- Meteorological data
- DEM pixel side 20 m
- Cartography of CORINE Land cover 1:100,000 (2004)

Extraction of raw materials:
- Actual location of extraction areas
- Location of the resources with data from the geological model
- Areas under protection that cannot be exploited

Infrastructures:
- Topographic maps 1:25.000 converted to ArcGIS format (IGN, National Geographical Institute)

Figure 5: Data compilation for different objectives.

2.3.3. Land evaluation modelling

Models are considered as simplified representations of the real world, which can be expressed in a wide variety of forms, such as conceptual diagrams, classification systems, and statistical or deterministic mathematical models. In land evaluation, empirical-based modelling has advanced from simple qualitative approaches to others which are based on 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 derived from existing literature sources (Cox and Madramootoo, 1998).

The development of Geographical Information Systems has greatly improved the possibilities of land evaluation modelling, and many different approaches have been described since the end of the seventies. However, land evaluation modelling requires the preliminary selection of a suitable mapping unit.

2.3.3.1. The mapping unit

At the scale of the analysis, a mapping unit represents a domain that maximises internal homogeneity and between-units heterogeneity. Various methods have been proposed to divide the landscape. All methods fall into one of the following groups (Guzzetti *et al*., 1999):

- *Grid-cells*, preferred by raster-based Geographical Information System 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 selection of an appropriate mapping unit depends on a number of factors, namely: the type of phenomena to be studied; the scale of the investigation; the quality, resolution, scale and type of the thematic information required; and the availability of the adequate information management and analysis tools.

In our case, two main map units are used. Grid-cells are used mainly for the location of sand and gravel deposits, groundwater vulnerability and doline susceptibility models, while unique-condition-units (homogeneous units) are used for the agricultural capability of the soil and erosion susceptibility models.

2.3.3.2. Land evaluation methodologies

The different land evaluation procedures can be classified in two main groups: qualitative and quantitative methods (Figure 6). Qualitative methods include qualitative approaches, expert systems and parametric systems. They are very flexible and permit a complete inclusion of expert knowledge. Unfortunately, they involve a great level of subjectivity, which implies that the maps produced by different researchers may be extremely different. Quantitative methods include statistical modelling, as well as recent approaches based on neural networks. Although a completely objective procedure does not exist, quantitative methods assure that the same results can be achieved provided that the same basic assumptions are made (Beguería and Lorente, 2003; de la Rosa *et al*., 2004; Guzzetti *et al*., 1999).

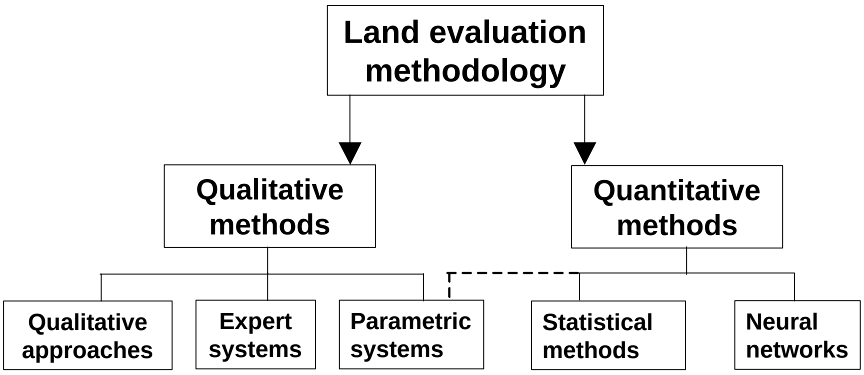


Figure 6: Land evaluation methodologies.

Qualitative approaches:

The matching of the land characteristics may be as simple as narrative statements of land evaluation for a determined geo-resource or geo-hazard (de la Rosa *et al*., 2004). A good example of this methodology is the erosion susceptibility model developed in chapter 5.1.

Expert systems:

Expert systems, such as artificial intelligence-based techniques, are computer programs that simulate the problem-solving skills of one or more human experts in a given field and provide solutions to a problem. These systems express inferential knowledge by using decision trees. The expert decision trees are based on scientific background (theoretical description) and results of experience and discussions with human experts (practical experience), and thereby reflect available expert knowledge. Decision trees are hierarchical multi-way keys in which the leaves are choices (classes/ranges), such as land characteristic generalization levels, and the interior nodes of the tree are decision criteria. These classification and regression trees are typical of soil and land resource surveys (de la Rosa *et al*., 2004). The MicroLEIS system developed by de la Rosa *et al.* (2004) present some models which are good examples of the application of this methodology (see chapter 2.3.3.4.). Gao and Alexander (2003), also applied this methodology in order to develop a sinkhole risk map (see chapter 2.3.3.5.).

Parametric systems:

Between qualitative and quantitative methods lie semi-quantitative land evaluations, derived from the numerically inferred effects of various land characteristics on the potential behaviour of a land-use system. Parametric methods can be considered a transitional phase between qualitative methods, based entirely on expert judgment, and mathematical models. They account for interactions between the most-significant factors by simple multiplication or addition of single factor indexes (de la Rosa et al., 2004). One of the most well-known examples of this methodology is the Universal Soil Loss Equation (Wischmeier and Smith, 1978) for erosion susceptibility (see chapter 2.3.3.5.).

Statistical methods:

In land evaluation, statistical systems are powerful empirical methods for predicting land suitability on the basis of selected land characteristics. Statistical approaches are data-based, 'black box' models, and their conclusions do not imply cause-effect relationships (but they can give certainty to well posed hypotheses). Given sufficiently good input variables, statistical modelling can provide successful results in a given area; however, its conclusions can hardly be applied to different places, or used to test simulation scenarios. The literature presents different multivariate statistical approaches including linear regression, discriminant analysis and logistic regression. The nature of the dependent and independent variables must suggest the selection of the most appropriate model (Beguería and Lorente, 2003). The logistic regression technique used in the project for the development of doline susceptibility model belongs to this kind of method (see chapter 5.2.).

Neural networks:

These artificial-intelligence-based technologies, which have grown rapidly over the last few years, show good capability to deal with non-linear multivariate systems. Moreover, they can process input patterns never presented before, in much the same way as the human brain does. Recently, connections have emerged between neural network techniques and its applications in engineering, agricultural, and environmental sciences (de la Rosa et al., 2004).

2.3.3.3. Interpolation methods

Interpolation is a complex issue, which consists of developing a continuous surface from punctual data. Thus, it is extremely important to select an objective model which leads to the best results. This election is not easy due to the methodological diversity (Chica-Olmo and Luque, 2002; Ninyerola *et al*., 2000; van Beurden and Riezebos, 1988; Vicente and Saz-Sánchez, 2002).

A fundamental step is the selection of the sample that should be dense, homogeneous in its spatial distribution and representative of the phenomenon to be analysed. A good review of sampling methodology may be found in Chica-Olmo and Luque (2002).

Interpolation procedures can be simple deterministic mathematical models (*inverse distance weighting, trend surface analysis, Thiessen polygons*, etc.), or more complex models (geostatistical methods, such as *kriging* and *thin plate splines*) (Ninyerola *et al*., 2000). Nonetheless, in most cases, these models do not take into account geographical information. There are more sophisticated methods that incorporate this kind of information, such as *co-kriging* and *elevation-de-trended kriging* techniques. But also multiple regression technique is used in the interpolation of punctual data, although, strictly speaking, this is not an interpolation method (Figure 7).

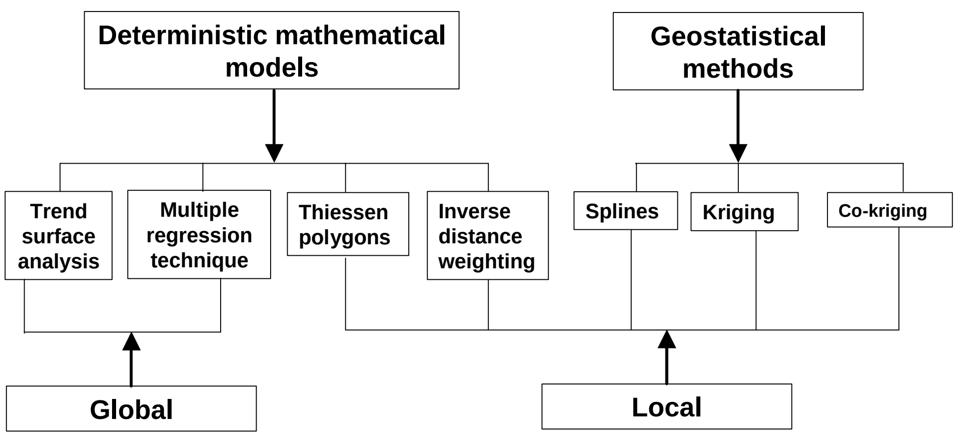


Figure 7: Interpolation methodologies.

Besides, it is also important to differentiate between global and local methodologies. In the first case all samples are used for the prediction, developing smoother models. These are inexact methods, as the prediction does not match the observed value in the sample. Good examples of global methodologies are *trend surface analysis* and *multiple regression analysis*. In the second case only part of the sample are used which should be previously determined; representative of these methodologies are *inverse distance weighting, Thiessen polygons* and *splines*. These methodologies are exact, as in this case, the predicted value matches the observed value in the sample (Vicente and Saz-Sánchez, 2002). The main interpolation methodologies found in literature are (Chica-Olmo and Luque, 2002; Ninyerola *et al*., 2000; van Beurden and Riezebos, 1988; Vicente and Saz-Sánchez, 2002):

- *Thiessen polygons:* the data from the polygons is obtained from the *Delaunay Triangulation*, similar to the Triangulated Irregular Network (TIN) structure in a Digital Elevation Model. Every polygon obtains the value from the point located inside it.

- *Trend surface analysis:* involves the adjustment by regression of a multiple polynomial function dependant on the coordinates.

- *Multiple regression technique:* is a variant of *trend surface analysis*, which takes into account other geographical information in addition to the coordinates.

- *Inverse distance weighting:* combines the proximity concept of *Thiessen polygons* with the gradual variation of the surfaces from *trend surface analysis*. The hypothesis is that the predicted value is a linear function of the neighbour date weighted by the distance.

- *Splines:* traditionally, these functions have been used in the adjustment of curves to experimental data. It is a particular variant of *kriging* that has been commonly used for the creation of Digital Elevation Models.

- *Kriging:* geostatistics constitute a theory about the statistical behaviour of natural phenomena with a spatial variability. Its fundamental concept is the regionalized variable, which can always be represented by a continuous surface over the map plane.

- *Co-kriging:* it is a variant of kriging which also takes into consideration other geographical variables.

2.3.3.4. Geo-resource evaluation modelling

Raw material: sand and gravels:

Throughout history, a fundamental concern in Geology has been to know how to translate geological knowledge to land-use managers, especially in the case of geo-resources, *i.e.* raw material management. A good review in the management of the geo-environment can be found in Lüttig (1994) and Becker-Platen and Preuss (1985).

The majority of examples in relation to raw-material modelling refer to the simple location of the resources and, in many cases, an estimation of its thickness or potential economical value according, for example, to the density of ornament. These surveys are usually carried out by means of questionnaires (de Mulder and Hillen, 1990, 1994; Küdig *et al.,* 1997; Wolden and Erichsen, 1990, 1994).

In The Netherlands, de Mulder and Hiller (1990) used Geographical Information Systems to develop environmental geological maps ranging in scale from 1:50,000 to 1:250,000. For gravel and coarse sand locations they developed a map on a scale of 1:100,000 showing the distribution, depth and quality of coarse-grained sand suitable for construction purposes. The thickness of the overburden was indicated as well.

The Geological Survey of Norway established a data-base for sand, gravel and hard-rock aggregate resources containing information about all deposits in Norway, also presented on resource maps, on a scale of 1:50,000 (Wolden and Erichsen, 1994).

The endeavours to produce resource maps in Spain have been limited to date. The IGME (actual ITGE, the Spanisch National Geological Institute) (1974) developed a series of analog maps of *Rocas Industriales* (industrial rocks) on a scale of 1:200,000. These maps depict the locations of raw material exploitation and the type and final use of the exploited material.

Geographical Information System techniques are only capable of producing two dimensional maps, thus they are a tool of limited value for geological modelling. The software Gocad (Earth Decision Sciences, 2005), developed for reservoir construction, solves this problem. It allows the creation and 3D-visualization of geological bodies and discontinuities. Functions especially designed for resource modelling computation (e.g. volume and thickness) make it useful for the 3D-construction of geo-resources and for vulnerability studies. Hoppe *et al*. (2006a) proved that the combination of Gocad for spatial modelling and ArcGIS for map creation is a favourable solution for geological modelling.

Thus, a geological 3D model of the Quaternary deposits for the location of sand and gravel resources in the surroundings of Zaragoza was developed by means of Gocad by Oswald Marinoni (Institute of Applied Geosciences of Darmstadt University of Technology). The information concerning sand and gravel thickness was extracted and introduced in ArcGIS for the model development. The same methodology was used for the creation of a model of overburden material thickness.

Protected and worth protecting natural areas :

In the study area almost all natural areas with environmental and geoscientific value are protected by environmental laws or land management planning. Therefore, the location of this resource is presented in the form of a simple cartography of these areas. In addition to this, other areas worth protecting and not included in the mentioned laws were digitalized.

Agricultural capability of the soil:

The first methods for land evaluation, after the FAO scheme (FAO, 1976), were mainly oriented to the edaphologic components. Afterwards, more economical approaches were developed due to the fact that, in many cases, a specific use is normally determined by economical parameters. Nowadays, the models tend to be more crop oriented. They try to determine the capability of the land for a particular type of crop. A good revision of methodologies can be found in Santé and Crecente (2005). In our case, our purpose is to determine the general land capability of the soil according to our final objectives, which are the introduction of the geo-resources maps as criterion maps in the land-use suitability analysis (see chapter 2.3.1.)

Most of the examples found in the literature in relation to general agricultural capability modelling with Geographical Information Systems are developed from the establishment of terrain units of unique-conditions. Cendrero *et al*. (1990) developed maps of homogeneous integrated units for the mediterranean provinces of Valencia and Gran Canaria (Spain). These units were defined on the basis of morphostructure, climate, lithology, superficial deposits, landforms, topography, active processes, soils, vegetation and human influence. Afterwards, the morphodynamic units were evaluated in terms of their soil capability and other qualities significant for planning.

De la Rosa and Magaldi (1982) from the IRNAS (Institute for Natural Resources and Agrobiology, Sevilla) developed the Cervatana model (C.S.I.C., 1996; de la Rosa *et al.*, 2002, 2004) that forecasts the general land-use capability or suitability for a broad series of possible agricultural uses. This model was developed with Mediterranean Region information, although other major components allow universal application. The spatial unit of the study or reference is the land-unit, which is defined from both the intrinsic characteristics of the soil and other ecological aspects as macro-topography, climate, current use and vegetation (de la Rosa *et al*., 2004).

In this model, following the generally accepted standards of land evaluation (Dent and Young, 1981; FAO, 1976; USDA, 1961), the prediction of general land-use capability is the result of a qualitative evaluation process or overall interpretation of the following biophysical factors: relief, soil, climate, and current use or vegetation.

This model was used in the current study since it had formerly been applied successfully in the surroundings of the study area at a lower scale (Machín and Navas, 1994, 1995; Navas and Machín, 1994, 1997a, 1997b). This implied the prior determination and mapping of homogeneous units.

The criteria used by different branches of landscape science for dividing into homogeneous units are: geomorphology, vegetation, soil (de Bolós i Capdevila, 1992). Amadio *et al*. (2002) emphasize the importance of geomorphology in landscape ecology studies. In fact, at the regional scale, their findings suggest that it is the physiography which best approximates the results of a landscape classification performed following a holistic approach. Taking this suggestion into account, geomorphology is the main criteria used in this project for such a division, followed by land cover, which synthesizes the climatologic and vegetation conditions.

2.3.3.5. Geo-hazard evaluation modelling

Erosion susceptibility:

In the last decades, many approaches to establish an erosion hazard model using Geographical Information Systems have been developed (Cox and Madramootoo, 1998; Cyr *et al*., 1995; Kertész, 1993; Le Bissonnais *et al*., 2001). A good example is Cox and Madramootoo (1998), who developed a soil loss model within a Geographical Information System environment in St. Lucia to evaluate agricultural management strategies, in terms of soil loss, on two agricultural watersheds. Cyr *et al*. (1995) introduce the use of remote sensing data for the classification of agricultural land-use and the percentage of ground cover, which plays a major role in the regionalisation of erosion.

The majority of models are based on the Universal Soil Loss Equation (USLE) methodology (Wischmeier and Smith, 1978) and subsequent derivations as RUSLE, USLE-M and so on (Cox and Madramootoo, 1998; Kinnell, 2001; Renard and Freimund, 1994; Shi *et al*., 2004). The Universal Soil Loss Equation is an empirical model developed by Wischmeier and Smith (1978) to predict long-term average annual soil loss from agricultural fields. It integrates six parameters that influence soil loss in the following relationship: average annual soil loss rate, rainfall erosivity, soil erodibility, slope length of the terrain, slope steepness, crop management and conservation practices made by man.

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 Universal Soil Loss Equation methodology (Wischmeier and Smith, 1978), introducing the following factors: erosivity of the rain, erodibility of the soil, topography and land cover. Also remarkable is the approach developed by I.C.O.N.A. (1987) in the Ebro Basin on a 1:400,000 scale. Although some authors, *i.e.* Desir (2001), agree that this methodology over-estimates the erosion rates when compared with experimental data. I.C.O.N.A. (1987) obtained erosion values of 200 tm/ha/year in the gypsum slopes in the central Ebro Basin using Universal Soil Loss Equation methodology, while Navas (1988) gave values of 81.7 tm /ha/year of salts exported by the Ebro Basin to the Mediterranean sea. In addition, Desir *et al*. (1992) obtained erosion rates of about 35 tm/ha/year in experimental parcels in gypsum slopes.

Renschler and Harbor (2002) pointed to the inconvenience of using this quantitative method based on empirical data to areas with different characteristics from the ones it was developed for, as it is the case in Mediterranean regions. Mati *et al*. (2000) conclude that the Universal Soil Loss Equation (Wischmeier and Smith, 1978) under-estimate or over-estimate the erosion amount depending on the vegetation cover.

Taking into account these factors and the final objective of this study (determining better location for different land uses, see chapter 2.1), it was decided to use a qualitative weighting method in order to differentiate between high and low susceptible areas but not to quantify the eroded material amount .

Thus, the methodology developed by van Zuidam and van Zuidam-Cancelado (1979), who studied the geomorphology of the central Ebro Depression in detail, was used. The fact that this methodology was developed in the surroundings of Zaragoza was also an additional reason for its selection. They developed an “ITC, International Institute for Geo-Information Science and Earth Observation, system of terrain analysis, classification and evaluation”. This is a system based on a landscape approach. The terrain is divided in terrain units or landscape units, and the parameters, as well as land qualities, may be rated, evaluated and classified, using aerial photographs, various thematic maps (e.g. topographic, soils), field work and expert knowledge.

The parameters introduced in the model match with the ones used in the majority of approaches revised. These are:

- Slope: slope steepness, slope length, slope form.
- Vegetation/Land use: vegetation density, land-use condition.
- Climatologic condition: heavy rainstorm frequency.
- 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 surface.
- Conservation practices: in plain, in drainage ways.

Doline susceptibility:

Many examples concerning subsidence hazard mapping can be found in the literature, especially in European and North-American developed countries. Using spatial analysis and experimental simulation, Soriano and Simón (1995) observed that, in the case of gypsum karst in the Ebro Basin, groundwater sulphate content, grain size of the detrital cover, Tertiary/Quaternary boundary topography, annual variation of the water table and of detrital cover thickness were the main factors controlling the development of dolines (see chapter 5.2.1. for more information about the dolines development process). Taking into account these variables, a theoretical spatial hazard model was elaborated, expressed as a mathematical equation, and a hazard map of their study area located upstream Zaragoza with a 1: 50,000 scale was created (Lamelas *et al.,* 2006a).

In subsequent studies Simón *et al*. (1998a,1998b) discovered that this model cannot be applied on a larger scale of 1:25,000 and used a qualitative assessment in stead. They introduced three main factors in the subsidence hazard, by order of importance:

- Topography of the Tertiary-Quaternary contact.
- Thickness of Quaternary sediments.
- Lutitic percentage in Quaternary deposits.

They also introduced the gradient in groundwater sulphate content as a secondary factor. With these factors they developed a potential hazard map. Afterwards, the potential hazard map was crossed with a cartography of present hazard, developed by air photograph analysis and cartography of dolines. The resulting map presents 7 categories of hazard from “Very high real hazard” to “Low potential hazard”.

Kaufmann and Quinif (2002) also employed a qualitative assessment for limestone karst in Tournaisis area, southern Belgium, already using Geographical Information System techniques. Hydrogeological data and geological mapping information were used to create the geo-hazard map. Records of former collapses were also available. These records were of great interest since doline distribution was obviously clustered in the area. This study showed that zones of high doline occurrence coincide with zones of heavy lowering of piezometric heads. Combining the density of former collapses with the dewatering of the limestone enabled them to delineate zones of low, moderate and high collapse hazard.

Green *et al*. (2002) also employed Geographical Information System technology to make a karst unit delineation. Many different overlays of the karst features were combined in order to achieve a better understanding of landscape dynamics.

Sinkhole[1] probability maps have also been developed for south-eastern Minnesota. These maps were constructed as paper maps, with boundaries drawn by the authors using subjective criteria. As part of the transition of this mapping effort into a digital Geographical Information System environment, Gao and Alexander (2003) developed a mathematical decision tree model for the construction of maps of relative sinkhole risk, based on the distribution of distances to the nearest sinkhole and the sinkhole density.

Whitman and Gubbels (1999) used Geographical Information Systems to investigate the spatial relationships between hydrogeologic factors and sinkhole formation near Orlando, Florida. Landsat TM imagery, digital topography, and well data were used to construct a model of head difference between a discontinuous set of superficial aquifers and the Florida aquifer, a regionally extensive confined aquifer.

Lei *et al*. (2001) studied sinkhole distributions influenced by karstification of bedrock, soil types and properties, groundwater condition, human activities, land use, infrastructures, and economic development. They developed a sinkhole hazard map using a qualitative weighting method within a Geographical Information System. They introduced three factors: water level in dry and rainy seasons, thickness of soil and finally the karstification of bedrock together with the fault distance.

In fact, in the last decade, several countries have built karst databases integrated in a Geographical Information System environment where new interpretations of the relationship between the causes of the data can be readily achieved (Cooper *et al*., 2001; Gao *et al*., 2001; Gao *et al*., 2005; Green *et al*., 2002; Lei *et al*., 2001). However, research studies referring to multivariate statistical analysis using Geographical Information System techniques for subsidence hazard mapping are scarce in comparison to other geo-hazards, *i.e.* landslide development.

This is one of the reasons for the decision to apply a logistic regression technique for the doline susceptibility map in the study area. At this stage, it is important to stress its main advantage: the possibility to analyse a qualitative variable (as the occurrence or not of dolines) as a function of several qualitative and quantitative explanatory variables, in comparison with multiple linear regression, which

[1] It is important to remark that the term sinkhole, widely used in American literature, only refers to collapse dolines, but not to slowly subsided areas. Thus, here, the term sinkhole is only used when the references use it, but not to refer to the process develop in our study area, as both features are present, collapse and subsidence dolines.

is appropriate only when the dependent variable and the explanatory variables are quantitative and continuous.

Groundwater vulnerability:

In the last decades, the importance of this resource as a driving force for economic development of urban areas all over the world caused the introduction of groundwater vulnerability maps in many studies oriented to land-use management under geo-environmental aspects (Cendrero *et al*., 1990; Dai *et al*., 2001; de Mulder and Hillen, 1990; Lerch and Hoppe, 2006; Wolden and Erichsen, 1990).

The European Commission set up the COST Action 620 on “vulnerability and risk mapping for the protection of carbonate (karst) aquifers”. COST stands for Cooperation in Science and Technology. The project was given additional impetus by the European Water Framework Directive, which is intended to provide a common framework for water resource policy and management (Andreo *et al*., 2006).

Definitions for the following types of groundwater vulnerability have been proposed by COST Action 620 (COST Action 65, 1995):

- Intrinsic vulnerability is the term used to define the vulnerability of groundwater to contaminants generated by human activities. It takes into account the geological, hydrological and hydrogeological characteristics of an area, but is independent of the nature of the contaminants.

- Specific vulnerability is the term used to define the vulnerability of groundwater to particular contaminants or group of contaminants.

Should a revision of methodologies be performed, it could be observed that most models deal with intrinsic vulnerability. They usually apply qualitative weighting methods taking into account the geological, hydrological and hydrochemical characteristics of the aquifer and the materials above it. (Aller *et al*., 1987; Cendrero *et al*., 1990; Doerfliger, 1996; Fobe and Goossens, 1990; Fredrick *et al*., 2004; Fritch *et al*., 2000; Malik and Svasta, 1999).

An example is the DRASTIC system developed by Aller *et al*. (1987), which considers the most important mappable technical parameters (factors) that affect groundwater pollution potential: depth to watertable (D), net recharge (R), aquifer media (A), soil media (S), topography (slope) (T), impact of the vadose zone (I), and conductivity of the aquifer (C).

Fobe and Goossens (1990) developed a groundwater vulnerability map for the Flemish Government. This map, on a 1:100,000 scale, was based on static factors, such as the lithology of the aquifer and its possible cover layers and the depth of the water table.

Cendrero *et al*. (1990) identified and mapped “integrated units” (homogeneous units) in *Canarias* and *Valencia* (Spain). These areas of descriptive nature were then evaluated in order to obtain diagnosis maps of groundwater vulnerability based on lithological characteristics and thickness of saturated zone.

For the Paluxy aquifer in Central Texas, Fritch *et al*. (2000) used the DRASTIC system and added data from variables such as land use/land cover to the other variables applied in this method, to generate subjective numerical weightings according to each variable´s relative importance in groundwater pollution susceptibility.

Fredrick *et al*. (2004) also adopted the DRASTIC indexing methodology, including the Analytic Element approach (developed in Minnesota University in 1978) to numerical ground-water flow modelling, in order to map groundwater vulnerability in Ischua Creek Watershed, Cattaraugus County, New York State.

All these methods are applicable to all types of aquifers, but they do not adequately take into account the special properties of karst aquifers. Methods such as EPIK (Doerfliger, 1996; Doerfliger and Zwahlen, 1998) and REKS (Malik and Svasta, 1999) were especially developed for karst.

Goldscheider *et al.* (2000) suggested that a method for vulnerability mapping at catchments scale should be applicable for all types of aquifers, as well as take into account the special features of karst. They developed the PI method based on the Geologisches Landsamt (GLA) method (Hölting *et al.,* 1995), which is applicable for all types of aquifers and provides specific methodological tools for karst.

COST 620 also proposed this method as one possibility of intrinsic resource vulnerability mapping, especially when detailed data are available. In this study, the general approach proposed by the German State Geological Surveys (GLA, Geologisches Landesamt, method) published by Hölting *et al.* (1995) is applied. It deals with intrinsic groundwater vulnerability and considers the karstic conditions of the study area which give rise to vulnerabilities. The basic idea of these authors is that the effectiveness of all natural processes in the protective cover for reducing contaminant concentration mainly depends on the travel time. As a consequence, the protective function is dependent on the main factors controlling travel time: the thickness of each stratum and the material properties (Goldscheider *et al*., 2000).

2.3.4. 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 at identifying the most appropriate spatial pattern for future land uses, according to specified requirements or preferences (Malczewski, 2004).

The Geographical Information System based land-use suitability analysis has been applied in a wide variety of situations including ecological and geological approaches, suitability for agricultural activities, environmental impact assessment, site selection for several facilities and regional planning (Hoppe *et al*., 2006a; Lamelas *et al.*, 2006c, 2006d; Malczewski, 2004; Marinoni and Hoppe, 2006).

Any planning process must focus on a mix of hard (objective) and soft (subjective) information. The former is derived from reported facts, quantitative estimates, and systematic opinion surveys. The soft information represents the opinions (preferences, priorities, judgments, etc.) of the interest groups and decision makers. The idea of combining the objective and subjective elements of the planning process in a computer-based system lies at the core of the concept of Spatial Decision Support Systems (Malczewski, 2004).

Spatial Decision Support Systems can be defined as an interactive, computer-based system designed to support a user or group of users in achieving a higher effectiveness of decision-making while solving a semi-structured spatial decision problem (Malczewski, 2004). Spatial Decision Support Systems also refers to the combination of sophisticated decision support methodologies and Geographical Information Systems (Marinoni, 2005).

Three major groups of approaches to Geographical Information System based land-use suitability analysis may be distinguished according to Malczewski (2004): (i) *computer-assisted overlay mapping*, (ii) *multicriteria evaluation methods*, and (iii) *AI* (Artificial Intelligence, soft computing or geo-computation) methods (Figure 8). The MCDM (*MultiCriteria Decision-Making*) procedures (or decision rules) define a relationship between the input maps and the output map. The procedures involve the utilization of geographical data, the decision-maker’s preferences and the manipulation of the data and preferences according to specified decision rules.

Different attempts to classify MultiCriteria Decision-Making methods by diverse authors exist in literature (Malczewski, 1999; Pereira and Duckstein, 1993; Vincke, 1986; Voogd, 1983). However, in general, most agree that decision rules can be classified into *multiobjective* and *multiattribute decision-making* methods. The *multiobjective* approaches are mathematical programming model oriented methods, while *multiattribute decision-making* methods are dataoriented. *Multiattribute* techniques are also referred to as the discrete methods because they assume that the number of alternatives (plans) is given explicitly while, in the *multiobjective* methods, the alternatives must be generated (they are identified by solving a multiobjective mathematical programming problem). In this study, since the alternatives are already predefined, the focus will be put on *multiattribute* techniques (Malczewski, 1999; Voogd, 1983).

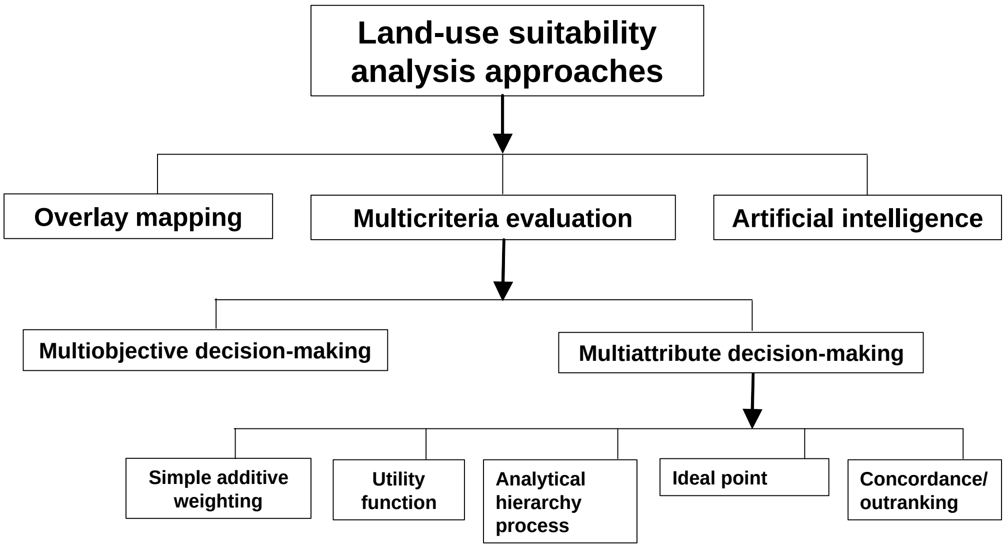


Figure 8: Land-use suitability analysis approaches.

Additive decision rules are the best known and most widely used MADM (*MultiAttribute Decision-Making*) methods in Geographical Information System based decision-making. Acording to Malczewski (1999), these are (Figure 8):

- *Simple Additive Weighting* (*SAW*) methods are the most often used techniques for tackling spatial *multiattribute* decision-making. These techniques are also referred to as *Weighted Linear Combination* (WLC) or scoring methods. They are based on the concept of weighted average.

- The *utility function* method is based on *multiattribute utility theory*. The term utility is a generic one: it includes both the concepts of utility and value functions. The value function approach is applicable in the decision situations under certainty (deterministic approach). Utility is a convenient method of including uncertainty (risk preference) into the decision-making process.

- The A*nalytical Hierarchy Process* (*AHP*) method, developed by Saaty (1977), is based on three principles: decomposition, comparative judgement, and synthesis of priorities.

- The *ideal point* method orders the set of alternatives on the basis of their separation from the ideal point. The ideal point can be considered as one of many possible points that can be used for ordering the set of feasible alternatives. For example, one may define the negative ideal point and measure the separation of the alternatives from that point.

- *Concordance* methods are based on a pairwise comparison of alternatives of which an ordinal ranking is provided. These methods are also known as *outranking techniques*.

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 site for a particular activity from a given set of potential (feasible) sites. The problem involves ranking or rating the alternative sites based on their characteristics, to identify the best site. Where there is no pre-determined set of candidate sites exist, the problem is referred to as "site search analysis" (Malczewski, 2004).

In this contribution both approaches are tackled. First, a site search analysis where every pixel represents one alternative is performed with S*imple Additive Weighting* method integrated in ArcGIS. Then, a site selection analysis is performed with the *PROMETHEE-2* methodology (Brans *et al*., 1986) using a set of predefined alternatives. All tools used in the project have been programmed and integrated within ArcGIS 9.1 by Oswald Marinoni.

In *Simple Additive Weighting* methods, the decision maker directly assigns weights of "relative importance" to each attribute. A total score is then obtained for each alternative by multiplying the importance weight assigned for each attribute by the scale value given to the alternative on that attribute and summing the products over all attributes (see chapter 6.1.).

The greatest disadvantage of the *Simple Additive Weighting* methods is that they tend to be *ad hoc* procedures with little theoretical foundation to support them. However, since they are easy to use, *Simple Additive Weighting* methods are actually quite widely applied in real-world settings.

PROMETHEE-2 belongs to the 'family' of *outranking techn*iques (*concordance methods*). This method uses preference function *Pj (a,b)*, which is a function of the difference *dj* between two alternatives for any criterion *j (*Brans *et al*., 1986*)*. Six types of functions based on the notions of criteria, namely, usual criterion, quasi criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area and gaussian criterion are proposed (see chapter 6.2.). A multi-criteria preference index (weighted average of the preference functions) can be calculated from which a ranking of the evaluated alternatives is obtained (Raju and Pillai, 1999).

The advantages of the concordance methods include the ability to consider both objective and subjective criteria and the requirement for the least amount of information from the decision maker. However, outranking techniques require pairwise or global comparisons among alternatives, which is obviously impractical for applications where the number of alternatives/cells in a database ranges in the tens or hundreds of thousands (Pereira and Duckstein, 1993).

Despite the existence of diverse methodologies, MultiCriteria Decision-Making methods have certain aspects in common. Alternatives represent the different choices of action available to the decision maker. Multiple attributes represent the lowest level of decision criteria. Decision weights are assigned to such attributes. Usually, these weights are normalized to add up to one (Gilliams *et al*., 2005).

Thus, a fundamental problem of decision theory is how to derive weights of a set of criteria according to their importance. An excellent and well-known weight evaluation method is the *Analytical Hierarchy Process*. This method, used in both approaches for criteria weights assignation, involves pairwise comparison to create a ratio matrix. Specifically, the weights are determined by normalizing the eigenvector associated with the maximum eigenvalue of the (reciprocal) ratio matrix (see chapter 6.1.). The procedure consists of three major steps: generation of the pairwise comparison matrix, the criterion weight computation, and the consistency ratio estimation (Saaty, 1977).

According to Marinoni (2004) “the integration of the *Analytical Hierarchy Process* in Geographical Information Systems combines decision support methodology with powerful visualisation and mapping capabilities which, in turn, should considerably facilitate the creation of land-use suitability maps”.

A general problem in the specification of the critera values for multicriteria evaluation is the subjectivity in its determination. Data which have been measured directly will certainly be regarded as more reliable than data which have been estimated, interpolated or simply interpreted. Thus, the method of data collection plays a central role (Marinoni, 2005). A stochastic approach, also developed by Oswald Marinoni, which takes account of the uncertainty of input values and which is used at a last step in this project could be a way out of this dilemma.

It is often hard to choose the input values for the *PROMETHEE-2* procedure since the criteria values usually can take a range of possible values. Acording to Marinoni (2005) “performing a *PROMETHEE-2* with the mean values gives some kind of mean result but one cannot quantify the uncertainty in either the input values or in the result”. Thus, Marinoni (2005) developed a stochastic approach, which uses probability distributions for the input parameters instead of single values (see chapter 6.3.).

The stochastic *PROMETHEE-2* approach first requires the assignment of theoretical distribution types to every criterion of the available alternatives. These distribution types can be determined through the analysis of the available data by using distribution fitting tests, like the *K-S-test*, the *chi2-test* or the *Anderson-Darling test*. Afterwards, these distribution types are used in *Monte Carlo simulations* in order to create a greater cuantity of values for each criterion of every alternative (Marinoni, 2005).

According to Marinoni (2005) “the number of repetitions or iterations (which is equivalent to drawing another random sample) should therefore be high enough for the following reasons: To avoid strong clustering around areas representing a higher probability and to ensure that also the ‘tails’ of a distributions are being sampled sufficiently”. Acording to Palisade (2002), 500 or more iterations are recommended in order to obtain accurate results.

Such iterations can easily be done simultaneously for various variables and various distributions by using simulation packages like @Risk (Palisade 2002), which work within common spreadsheet programs and allow an easy performance of *Monte Carlo simulations* within a familiar software environment (Marinoni, 2005).

3. General characterization of the study area

The study area of this project, located in the Aragon Region is limited in the north by a gypsum scarp of the Zaragoza formation, in the south by two calcareous structural platforms, *La Muela* and *La Plana*, and in the west and east by the *Jalón* and *Ginel* Rivers respectively (Figure 9, Map 1, 2). This area covers about 900 km^2, was deemed suitable for this research since many of the aspects that play an important role for land-use management are represented:

- Increasing urban and industrial development which results in a rising demand for land and raw materials (*i.e.* sand and gravel) for construction purposes.
- The intensive agricultural irrigated land requiring the best environmental conditions to be productive.
- Existence of natural areas of great environmental and geoscientific value worth protecting and exploiting in the best way.
- Numerous geo-hazards (doline development, erosion, etc.) which should be considered in all land-use management planning.

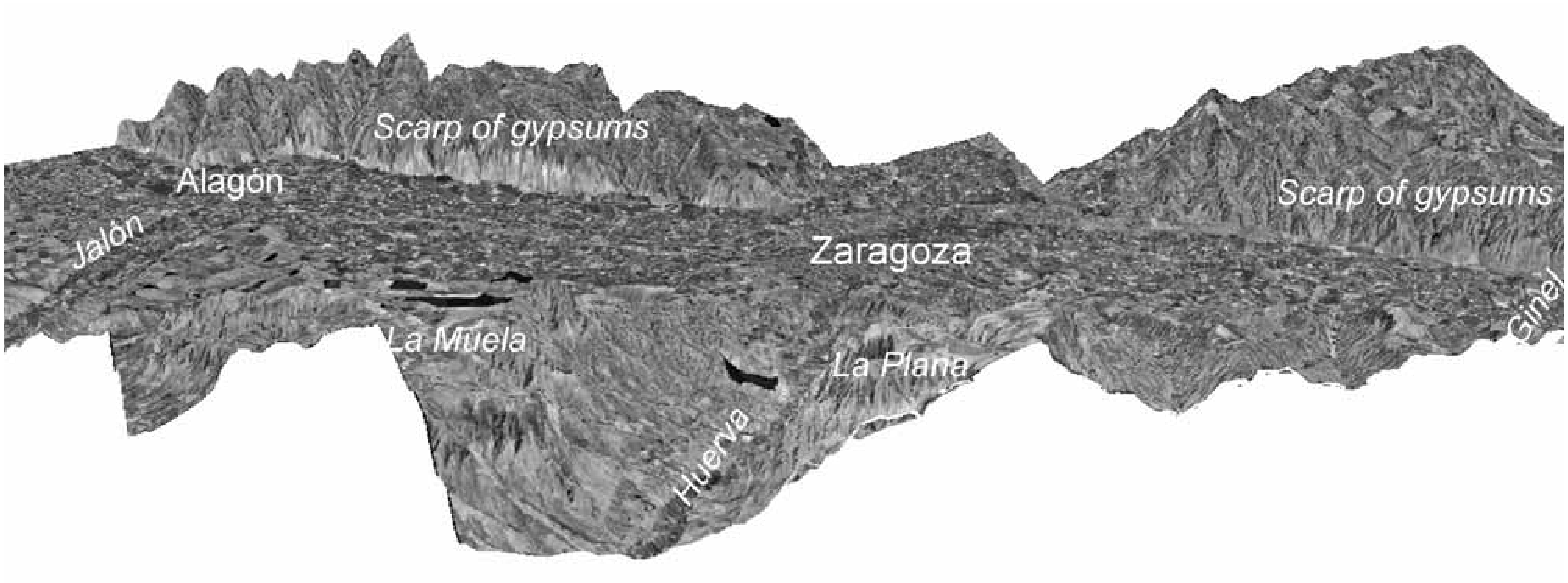


Figure 9: Three-dimentional representation of the airphotograph from the *SIG oleícola* (M.A.P.A, 1997) in the study area

3.1. Physical environment

3.1.1. Climate

The Ebro Basin constitutes a wide corridor which connects the Mediterranean Sea and the Atlantic Ocean. Despite the great diversity of climates existing in the basin, the central sector shows semi-arid characteristics with mean annual precipitation of about 350 mm and a mean annual temperature of about 15°C (Figure 10). Thus, the surroundings of Zaragoza present a Continental Mediterranean climate characterized by an irregular distribution of precipitation (Cuadrat, 1999; Frutos, 1976; Saz-Sánchez, 2003).

Precipitation values reach two maxima during the year, in spring and autumn, separated by long periods of drought. Precipitation values also vary between different years. In addition, the periods of low precipitation correspond to the months of more elevated temperatures, emphasizing even more the semi-arid character of this climate.

Another characteristic of the local climate is the high thermal difference between summer (average monthly maximum temperature of 24-25°C in July) and winter (monthly minimum temperature of 5-6°C in January) of about 18°C.

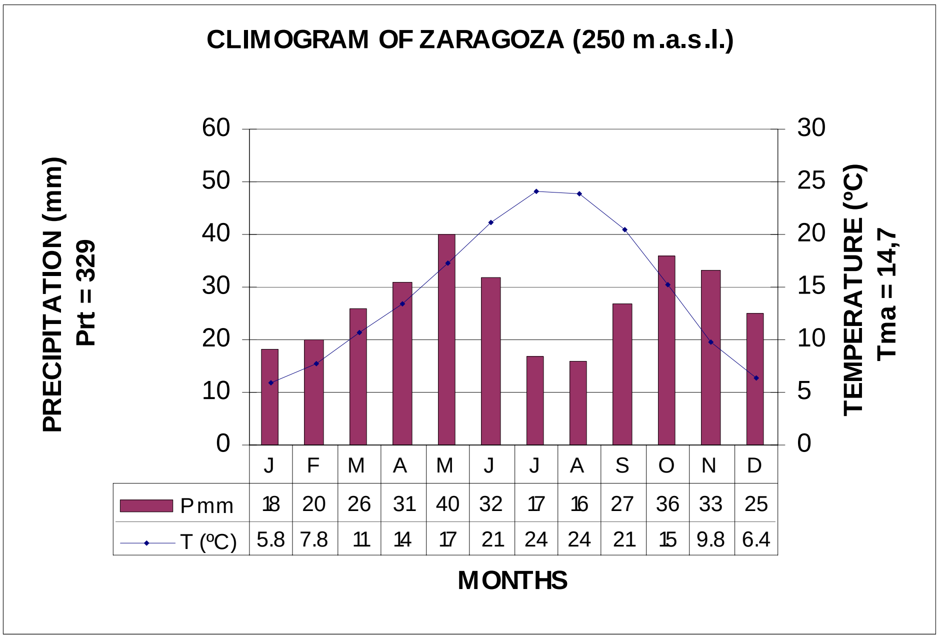


Figure 10: Climogram of Zaragoza. Source: Aragon Government.

The typical persistent fogs are linked to the existence of an anticyclone in the north of Europe and the special topography of the Ebro Basin.

Another important characteristic is the intensity and frequency of the wind called *Cierzo* (NW wind) which lowers the apparent temperature felt by people by about eight degrees (Cuadrat, 1999). This wind is more or less constant throughout the year, but more present in cold periods, while the wind coming from the E-SE (called *Bochorno*) is the dominant in summer and spring.

3.1.2. Geology

Zaragoza city is located in the central part of the Ebro Basin, in the north-east of the Iberian Peninsula (Map 1). The triangularly shaped Ebro Basin is limited in the north by the Pyrenees, in the south-west by the Iberian Range and in the south-east by the Catalan Coastal Range. The basin was formed as consequence of the deformational history of these peripheral mountain ranges during the Alpine Orogenesis (Alberto *et al*., 1984).

The Ebro Basin is the southern foreland basin of the Pyrenees, an alpine orogen formed in a continental collision zone. Like most foreland basins, the basin was generated by flexure of the continental lithosphere induced by vertical loading of the Pyrenees orogenic wedge.

During the initial sedimentary stage, during the Paleocene–Eocene, the basin was open to marine transgressions with continental and marine sedimentation that took place in exorheic conditions (Alonso-Zarza *et al.*, 2002; Gutiérrez-Elorza and Gutiérrez-Santolalla, 1998; Riba *et al*., 1983).

The second stage in the sedimentary evolution of the Ebro Basin (Upper Eocene–Miocene) began during the Priabonian Regression (Upper Eocene). After this period the sea had retreated from the Ebro Basin, which then developed into an individual endorheic basin surrounded by topographic heights (Riba *et al*., 1983). During this endorheic stage, the unroofing by tectonic uplift and erosion of the surrounding mountain ranges provided detritus (molasses) which was deposited in alluvial fans, distally related to shallow lacustrine environments with evaporitic (playa-lake) and carbonate sedimentation (Benito *et al.,* 1998) (Figure 11).

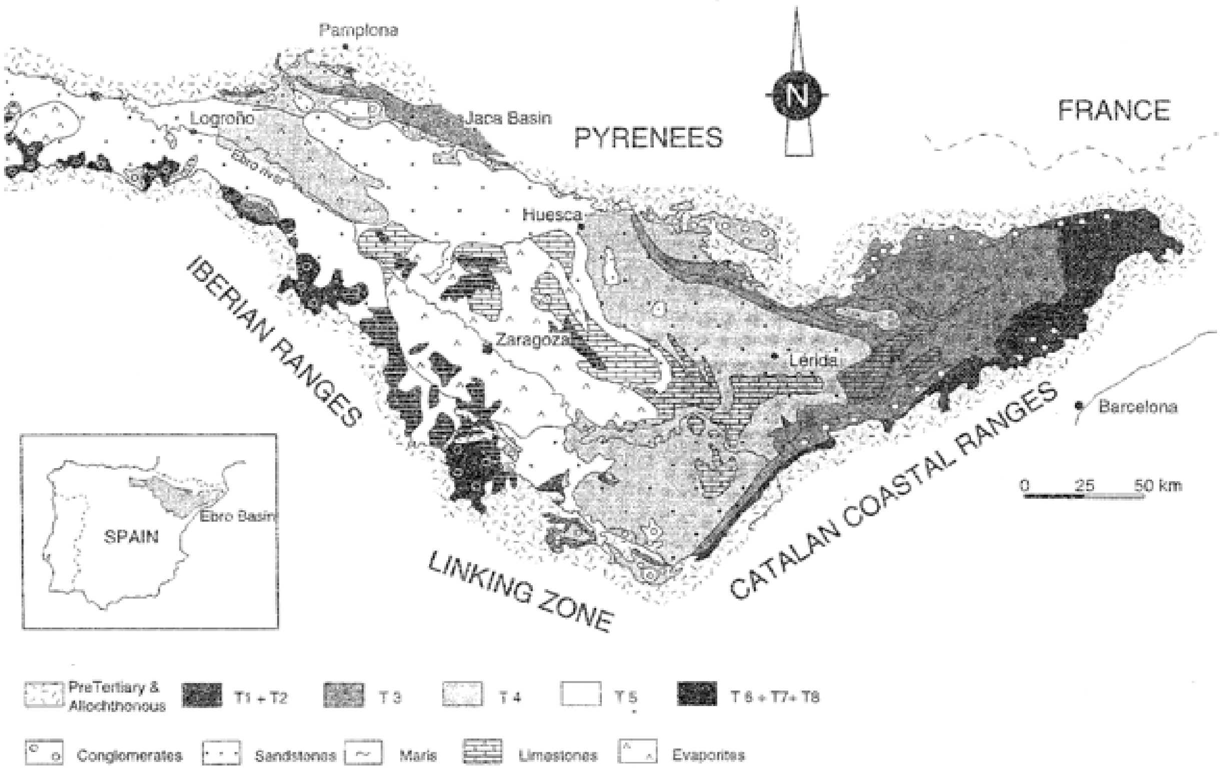


Figure 11 Geological map of the Ebro Basin tectosedimentary units (T1-T8) with lithofacies (mappable facies associations) distributions for every unit. Source: Alonso-Zarza *et al*., 2002.

The continental sedimentary infill of the basin is composed of conglomerates and sandstones at the margins grading into clays, marls, evaporites and carbonate facies towards the depocentre of the basin (Benito *et al*., 1998). Throughout the tecto-sedimentary evolution of the basin, the main evaporitic formations have developed in the most actively subsiding depocenters which have migrated from north to south (Benito *et al*., 1998; Ortí, 1990) as a consequence of continued convergence and forebulge translation.

In the central part of the basin, these playa-lake deposits, from the Zaragoza Formation (Upper Oligocene-Lower Miocene), form the greatest gypsum outcrop in the area that is divided into three sectors, *Retuerta*, *Mediana* and *Alfocea* by the Ebro and *Gállego* Rivers (Ortí, 1990; Quirantes, 1978; Riba *et al*., 1983). It is a thick sequence comprising upto 3000 m of gypsum (with anhydrite in depth). The Upper Unit (Figure 12) is 600 m thick and is composed of a lower 140 m thick clay-marl subunit, an intermediate 120 m thick halite subunit (its upper boundary ranges from +95 m in Zuera to +23 m.a.s.l. in Tauste) and an upper anhydrite-gypsum subunit (Torrecusa and Klimowitz, 1990). The detailed distribution of the different lithological bodies of the Upper Unit is not well known, since facies show abrupt lateral and vertical changes, and most information come from interpretation of four petroleum logs and three logs (see Figure 12).

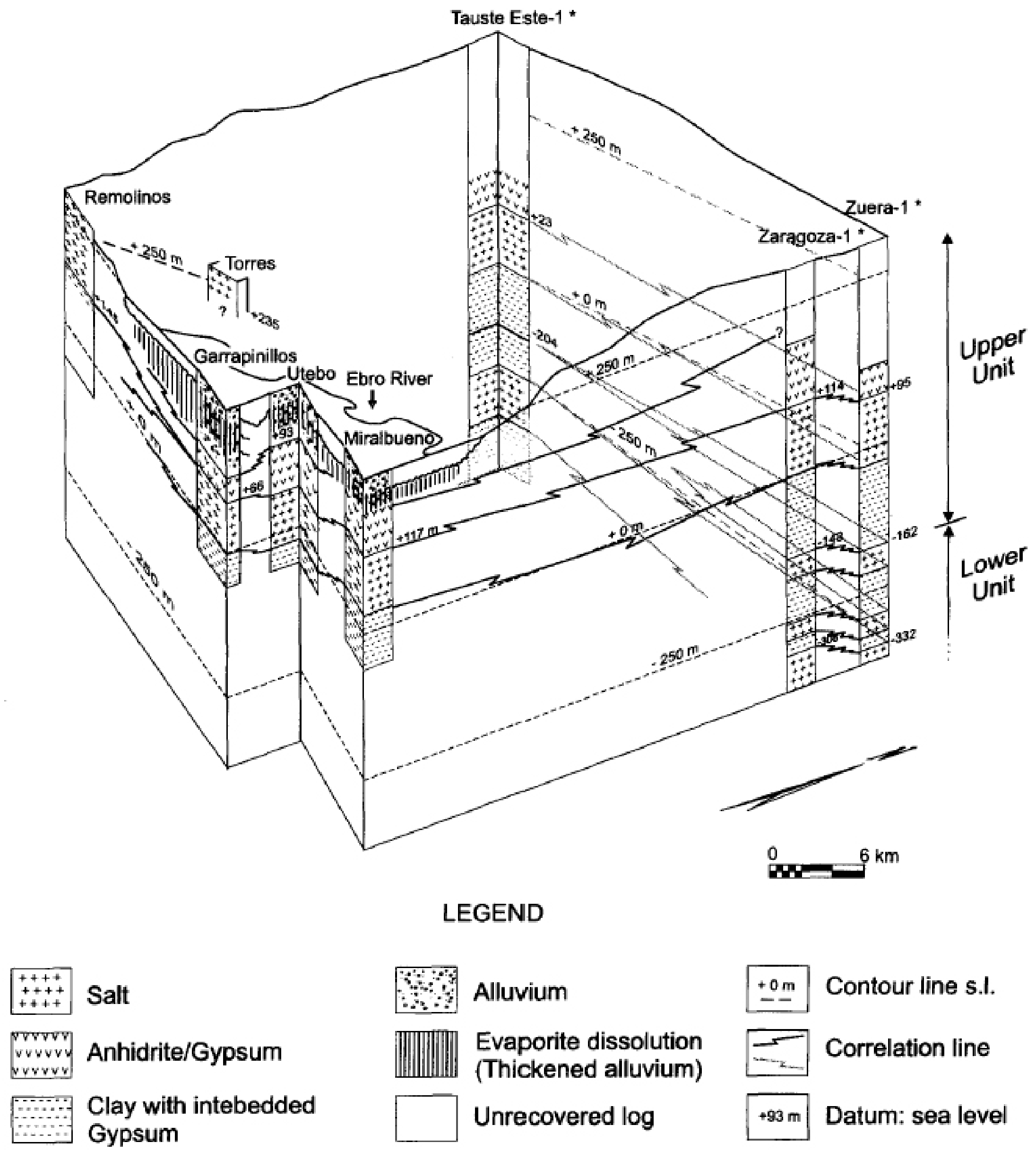


Figure 12: Fence diagram based on the stratigraphical relationships delineated by Torrecusa and Klimowitz (1990), using gamma-ray logs in *Tauste* Este-1, *Zaragoza*-1 and *Zuera*-1, and by Esnaola *et al*. (1995), using the strip logs performed by Tosla S.A. in *Remolinos, Torres, Utebo, Garrapinillos* and *Miralbueno*. Source: Benito *et al*., 1998.

By the end of the Miocene, or the beginning of the Pliocene, a proto Ebro River captured the depression, which consequently lost its endorheic character. Throughout the Quaternary, the pediments and terraces were deposited above the evaporitic deposits forming an alluvial aquifer which contributes to active and permanent karst processes.

3.1.3. Geomorphology

The Ebro River is the main Mediterranean fluvial system and flows through the Ebro Depression. The incision of the Tertiary sediments by externally draining river systems generated the main present-day geomorphological features of the Ebro Depression (Alberto *et al*., 1984; Benito *et al*., 2000; Desir, 2001; Gutiérrez-Elorza *et al*., 2002; Gutiérrez-Elorza *et al*., 1982; Gutiérrez-Elorza and Peña, 1994; IGME, 2005;

Mensua and Ibañez, 1977; Pellicer and Echeverría, 1984; Peña *et al*., 2002; Soriano, 1990; van Zuidam, 1976; Yetano, 1978).

Today, about a third of the depression is covered by Quaternary deposits. The most widespread of these sediments are covered pediments and fluvial terrace deposits commonly crowned by calcretes. There are also infilled valleys, talus flatiron sequences, lacustrine saline deposits and aeolian sediments.

The main geomorphological structures present in the study area, according to the Geological map scale 1:50,000 (I.T.G.E., 1995, 1998a, 1998b, 1998c, 1998d), are:

- Structural platforms: mantled pediment deposits, locally known as *muelas* or *planas,* capped by almost horizontal limestone, which locally mark the end of Tertiary internal drainage sedimentation. *La Plana de Zaragoza* and *La Muela de Zaragoza* (Map 2) in the study area are two structural platforms located to the south of the city. They are the highest points in this sector at 675 and 695 m.a.s.l., respectively. Both structural platforms are subhorizontal, slightly inclined towards the Ebro River and have similar characteristics, since their origin corresponds to a single platform, which was incised by the *Huerva* River (Figure 13).

Figure 13: General view of the study area from the north-west near *Juslibol*. On the left is the scarp of gypsums in the north-west of Zaragoza, which towers can be seen in the top middle-left sector. In the middle the flood plain and on the top right the two structural platforms. May 2004.

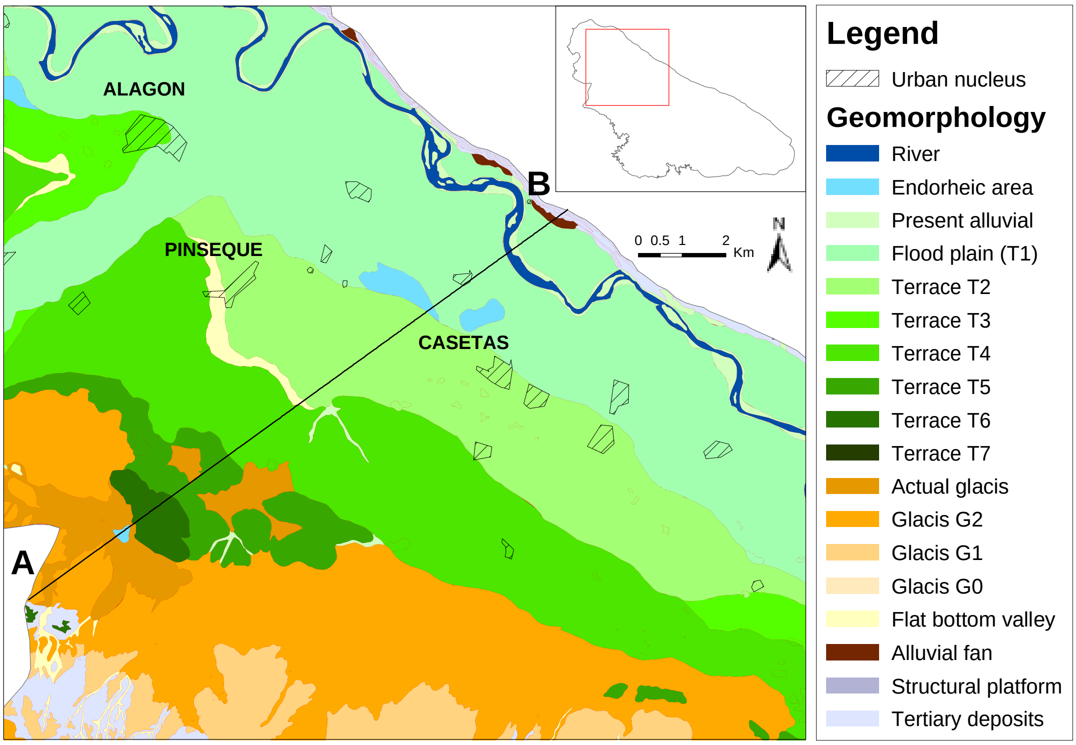
- Slopes in Tertiary materials: rounded hills developed in Tertiary silts, clays, marls, sandstones and gypsum materials of scarce elevation and crossed by flat bottom valleys. These Tertiary materials are highly degraded by erosion processes and covered, in many places, by extensive pediment levels developed at the foot of the structural reliefs. In the north or the study area, these Tertiary materials present a rough scarp in the contact with the Quaternary (Figure 14).

- Pediments: the Quaternary pediments or glacis are composed of calcareous pebbles and gravels (angular clasts) in a silt-argilleous matrix. The amount of calcium carbonate increases with the relative age of the pediment surface and deposit, so that thick, well developed calcified horizons are found on the oldest and highest pediment levels. According to the geologic map scale 1:50,000 (I.T.G.E., 1995, 1998a, 1998b, 1998c, 1998d), four different levels can be recognised in the study area. Three of these levels belong to the Pleistocene and present a thickness of about 10-15 m. The last level, more recent, belongs to the Holocene period and has a thickness of 2 or 3 m (Figure 15).

Figure 14: Slopes in Tertiary materials covered by sclerophyllous scrubs on the north-west of Zaragoza city, near *Juslibol*. May 2004.

Figure 15: Pediment overlaying the Tertiary gypsums in a sector on the south-west of Zaragoza city. May 2004.

- Fluvial terraces: these corresponds to gravels, sands, silts and clays deposited by the Ebro River and four of its tributaries: *Gállego, Huerva*, *Jalón* and *Ginel* Rivers. The *Gállego*, 193.2 km long, originates in the Pyrenees, while *Jalón* and *Huerva* rivers, 223.7 and 132.6 km length respectively, rise in the Iberian Range. Unique among the aforementioned tributaries is the *Ginel* River which is 10.2 km long and originates in the *La Plana* structural platform. Eight levels of terraces with heights of 5 (flood plain-T1), 10-13 (T2), 20-25 (T3), 35-40 (T4), 45 (T4B), 65 (T5), 90 (T6) and 120 (T7) m above the river level can be discerned in the study area (I.T.G.E., 1995, 1998a, 1998b, 1998c, 1998d). In some sectors these deposits are affected by synsedimentary subsidence due to underlying dissolution of evaporitic Tertiary bedrock. Thus, the thickness of these deposits varies from few meters up to more than 60 m (Figure 16 and 17).



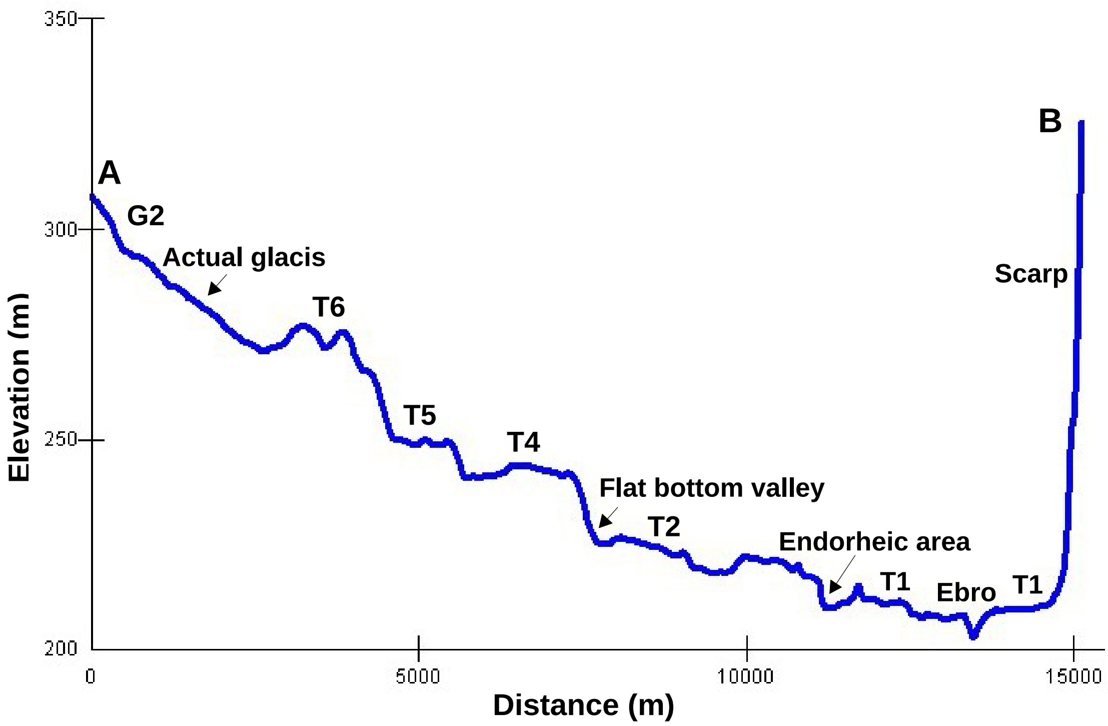


Figure 16: Profile of the Ebro River terrace levels downstream *Jalón* river.

Figure 17: Terrace of the *Gállego* River on the north of Zaragoza affected by a paleo-collapse. May 2004.

- Flat bottom valleys: these valleys, locally called *vales*, form a wide drainage network. They are orientated in a NE-SW direction and are slightly inclined towards the Ebro River. The origin of these valleys is related to their filling with gypsiferous pebbles, silts and clays from the surrounding hills. The thickness of the fillings is significant, up to even 15 m (Figure 18).

- Alluvial fans: these deposits connect the slopes of the Tertiary hills with the alluvial terraces in the drainage areas of the flat bottom valleys, and are composed of Quaternary pebbles, sands and silts (Figure 19).

- Endorheic areas: these poorly drained closed depressions are composed of gypsiferous silts and clays and are found throughout the Ebro Basin. In some cases, these depressions are temporarily or permanently filled with water. This is the case with a number of small depressions present in the study area, which are filled with water, in some cases, due to their connexion with the aquifer (Figure 20). However the big endorheic areas mapped in the Geological map (Map 1a and 2) are not usually filled with water.

Figure 18: *Vales*, flat bottom valleys at the south of *La Cartuja* direction to *Valmadrid*, which take their name from the geomorphological characteristics of the landscape. Between these vales appear the slopes in Tertiary materials. Photo by Andreas Deckelman and Christian Tigler. March 2006.

Figure 19: Alluvial fans in contact with the Tertiary gypsums slopes at the south of *El Burgo de Ebro*. Photo by Andreas Deckelman and Christian Tigler. February 2006.

Figure 20: Closed depression filled with water on the north-west of *La Venta del Olivar*. October 2004.

- Flood plains: the river valleys in the study area basically form a meandering pattern with an extensive floodplain. This is especially so in the case of the Ebro River, which shows an asymmetry between both banks. Upstream of Zaragoza, the Ebro River flows close to the Tertiary gypsums, which present a rough scarp in direct contact with the flood plain on the the left bank (Figure 13). In contrast, up to seven levels of terraces are developed (Figure 16) on the right river bank. On the other hand, in the sector downstream of Zaragoza, the flood plain is more extensive on both banks (Figure 21), presenting up to two levels of terraces and a good network of alluvial fans. As a result of its meandering pattern, the Ebro River has left a great number of abandoned meanders and several oxbows of great value from an ecological point of view (Figure 22).

Figure 21: Floodplain downstream Zaragoza in the vicinity of *La Cartuja*. March 2006.

Figure 22: Oxbows in *La Alfranca, Pastriz* and *El Burgo de Ebro* downstream Zaragoza city. March 2006.

3.1.4. Hydrogeology

The Quaternary deposits of the Ebro River in the surroundings of Zaragoza form an unconfined alluvial aquifer with a high degree of permeability and a high water table level. The characteristics of this aquifer have been widely studied in the past for protection purposes, but also for administrative purposes due to the demand for knowledge about the size of the water resources (Bielza de Ory and Martínez-Gil, 1994; Martínez-Gil, 1995; Octavio de Toledo, 1986; Octavio de Toledo and Arqued, 1990; Sahuquillo, 1976; Sánchez-Navarro *et al*., 2004). All these studies on the geophysical characterization of the alluvial aquifer, have referenced two publications by the National Geological Institute (ITGE) from the 70s and 80s (IGME, 1978, 1981). The Ebro River Authority (CHE, *Confederación Hidrográfica del Ebro*) has developed a Water Point Inventory database (IPA, *Inventario de Puntos de Agua*), in relation to water table data and information about hydrochemical characteristics of groundwater, which gathers all the information collected by previous studies.

The Quaternary aquifer is mainly composed of siliceous and calcareous gravels and sands. The permeability in the alluvial terraces (or, in a strict sense, the alluvial aquifer) is high or very high, varying between 10 and 100 m/day, while in the pediments it is medium-low and varies between 1 and 100 m/day.

The recharge of the aquifer is mainly determined by the water supplied by irrigation, estimated in the area in more than 10,000 m^3/ha. About 50% of water used for irrigation is infiltrated to the aquifer (Martínez-Gil, 1995). Precipitation recharge plays a secondary role and the aquifer drains into the river, which means that the water flows from the different terrace levels to the river. Thus, apart from some loss of water from the water supply network and precipitation, irrigation water represents the major water input to the aquifer.

The volume of water extraction is much lower than the recharge. Industry is the greatest groundwater consumer in the study area, extracting about 40 hm^3 /year. This high value only represents quarter of the potential extraction.

The water table level is located between the 160 and 240 m.a.s.l., and is subject to extreme annual variation between summer and winter due to the dependence of the recharge to the irrigation.

In general, groundwater pH is about 7.5, and conductivity ranges between 1500 and 3000 µS/cm. The Ca^{2+} concentration of the water is high, varying between 150 and 300 ppm. Both SO_4^{2-} concentrations (350-1000 ppm) and Na^+ concentrations (120-260 ppm) are also very high. On the contrary, HCO_3^-, Mg^{2+} and K^+ concentrations are lower (300, 40-100, and 3-8, respectively).

In literature, not much attention has been paid to the Tertiary aquifer, which consists of two different materials: firstly, the gypsiferous materials with mean-low permeability (between 10 and 0.1 m/day) due to porosity between particles. The high solubility of its materials determines the bad quality of the waters due to high conductivities. And secondly, the marly-gypsiferous materials of low permeability (between 1 and 0.1 m/day). These behave as an impermeable layer (Martínez-Gil, 1995).

3.1.5. Vegetation

According to Braun-Blanquet and de Bolós (1987) two climatic domains which correspond with two vegetation levels exist in the study area. These two levels, named according to the main species present, are:

- *Juniperus thurifera* level, of Mediterranean Steppe climate, located below 350-400 m.a.s.l. The climatic community, *Rhamneto-Cocciferetum thuriferesum*, is a scarcely dense shrub of the species *Rhamnus lyciodes* and *Juniperus thurifera,* which appear very rarely nowadays due to the antrophic degradation of the forest in this area.

- *Pinus halepensis* and *Quercus coccifera* level, of Mediterranean Semiarid climate, located between 354-400 m.a.s.l. and 700 m.a.s.l. represented by the sub-associations *Pistacietosum cocciferetosum* and *Caricetosum humilis*

This sequence of levels does not match with the climatologic sequences of forest formations described by Rivas-Martínez (1987), but combines perfectly with the special conditions of thermal inversion appearing in the central sector of the Ebro Basin.

Nowadays, the associations actually present in the Tertiary gypsum slopes are *Helianthemum squamatum* and *H. levandulaefolium*, *Helichysum staechas, Koeleria sp., Ligeum spartum, Salsolo vermiculata, Stipa tenacisima, Broma rubens.*

The vegetation cover differs a little from the vegetation in the gypsum slopes in the highest levels of the Ebro River terraces and in the structural platforms. At about 60-70%, the percentage of cover is also higher here. The characteristic species of this areas are *Rosmarinus officinalis, Thymus vulgaris* and *Brachypodium ramosum*.

A wide variety of forests and shrubs exist along the river banks of the main rivers (Ebro, *Gállego, Jalón, Huerva* and *Ginel*). *Tamarix gallica, Populus alba, Salís purpurea, Phragmites australis and Sauceda altísima* are the most frequent species.

Map 3 shows the spatial distribution of the vegetation, according to the forest map scale 1:50, 000 from Aragon Government (D.G.A., 2001).

3.1.6. Soils

There are several studies describing and mapping the soils of the study area (Alberto *et al*., 1984; C.S.I.C., 1970; I.C.O.N.A., 1990; M.A.P.A., 1978). Though the scale of work of these studies is not as detailed as required for our final objectives, these studies provide very good information on the general characteristics of soils in the central sector of the Ebro Basin.

More recent studies have been performed in the study area at a more detailed scale (Artieda, 1996; Desir, 2001; Machín and Navas, 1994, 1995, 2002; Navas and Machín, 1994, 1997a, 1997b). According to these studies, the main type of soils present, following the last version of the F.A.O. classification (FAO, 1998), are:

- Leptosols: located in the hills and slopes, generally in areas with high slopes prone to the existence of erosion processes. They develop in compacted lithologies, mainly in the gypsums of the Zaragoza formation or limestones. Usually found in the crest and talus of gypsiferous hills. They are shallow soils, of no more than 20 cm depth, with an AB profile and a high proportion of rocks. They also have very high gypsum content, are moderately saline and have a low organic matter content .

- Gypsisols: soils developed on alluvial-colluvial gypsiferous materials, mainly located in the flat bottom valleys. They are deep soils with an ABC type profile. In general, they are poorly developed and their texture is mainly silty with very few stones, as well as a low organic matter content . Gypsisols normally have a gypsic horizon that, sometimes, has petric characteristics. These soils are very erodible.

- Calcisols: located in high terraces and glacis. They are also deep soils, between 60 and 100 cm depth, with ABC type profile. The main characteristic is the presence of calcareous crusts and high content of stones. The drainage conditions are good and the erosion risk not very high.

- Cambisols: located in low pediments, in marly and gypsiferous materials, they are well developed with an ABC type profile. They have medium or high rockiness depending on their origin and silty loam texture. The drainage conditions are also good and the erosion risk is low.

- Regosols: developed on gypsiferous unconsolidated coluvial material. They have an ocric A horizon, a silty loam texture and low fertility. They also retain the gypsiferous characteristics in the upper 50 cm and are developed on medium slopes, where erosion is relatively important.

- Fluvisols: developed in recent alluvial zones, located mainly in the flood plain of the rivers. They are very young soils with a profile determined by the depositional conditions more than by edaphogenic factors.

- Solonchaks: mainly located in the shallow depressions and some reaches of the flat valley bottoms. They have salic properties and in some cases poor drainage. These soils are deep and stoneless and their texture is mainly silty clay.

3.1.7. Geo-resources

The Quaternary deposits of the rivers located in our study area (Ebro, *Gállego, Jalón, Huerva*) represent a valuable geo-resource in terms of sand and gravel deposits. These raw materials are used mainly for infrastructures and construction purposes and are the only ones exploited nowadays in the area of study. In addition to this, gypsum and salt are also worked in the surroundings.

In fact, sand and gravel extraction is one of the main subsectors inside the mining industry in the Spanish territory, because of its productivity and intrinsic value. This is true especially for the study area due to the great amount of resources and the continuous urban and industrial development (Figure 23).

Figure 23: Big sand and gravel extraction site in the vicinity of *Garrapinillos* in Terrace level T4. November 2005.

The degree of economic interest in the different terraces of the Ebro River increases with the distance to the actual river bed. The terraces T4, T5 and T6 (according to definition of the Geological map from ITGE) are especially interesting with respect to sand and gravel extraction (Manso *et al*., 2001). The pediments are also deposits of sand and gravels, but are not interesting for the extraction industry due to their low quality.

Taking advantage of this resource implies conflicts with other land-use interests that accompany the fast urban industrial development of the region, as well as the existing agricultural uses, which also traditionally occupies the terraces.

Moreover, these deposits contain substantial groundwater resources. Throughout history, the existence of water has meant a driving force for economic development. However, today, this resource that should be preserved for future generations is being threatened by this development, due to the demands of materials by the construction industry (Figure 24).

Figure 24: Extraction site arriving at water table level in the surroundings of *Garrapinillos*. November 2005.

Another important geo-resource in the area is the soil in relation to its suitability for agricultural use. Soils can be used for almost all agricultural purposes, if sufficient inputs are supplied. External inputs or improvements are expressed in terms of capital, energy, or environmental costs.

However, due to the semiarid characteristics of the climate in the surroundings of Zaragoza, the soils are very fragile and, because of their low organic matter content, poor structure and sparse vegetation cover, they are prone to be very easily eroded. Thus, every human impact may have serious environmental consequences, which could finally lead to desertification (Navas and Machín, 1997b).

Actually, this resource has been threatened in the last decades by the construction of many infrastructures in low terraces of the rivers which traditionally had been occupied by the long-established orchard (Figure 25, 26). According to de la Rosa *et al*. (2004), the main aim of soil protection should be to minimize the socio-economic and environmental costs of improving productivity, by predicting the inherent capacity of a soil unit to support a specific use and management for a long period of time without deterioration. Moreover, the fragility of the soils demands for profound knowledge of their capacity to sustain different uses, namely agriculture, for its conservation and maintenance of the landscape.

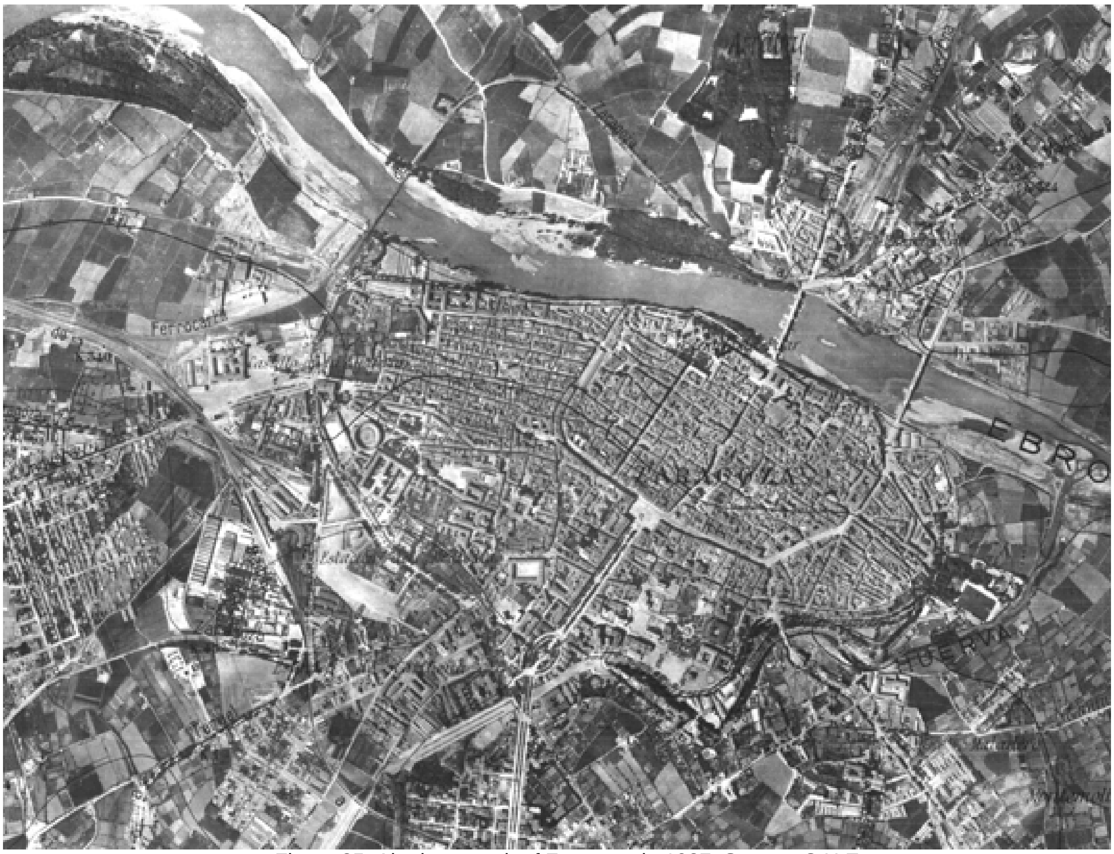


Figure 25: Air photograph of Zaragoza in 1927. Source: C.H.E. (ftp://oph.chebro.es:2121/BulkDATA/FOTOPLANOS1927/fotoplanos.htm).

Figure 26 Air photograph of Zaragoza city in 2004. This indicates how the city has grown in the 20th century to the north and west occupying the flood plain traditionally occupied by the orchard.

Finally, but not less important, landscape must be considered as a highly important resource. This is essential not only from the point of view of the observer, but also from its scientific value, as the environment contains essential habitats for the conservation of species, in some cases, in danger of extinction.

In fact, several areas included in the Natura Network 2000 are found within the study area (Figure 27). This network is the most important initiative to protect sites, based on scientific criteria. It includes Special Protection Areas (SPA) for birds, established by the Birds Directive (79/409/CEE), and Special Areas of Conservation (SAC) to be designated for other species, and for habitats, established by the Habitats Directive (92/43/CEE).

In addition, in the last years there has been an increasing international concern about the geological and geomorphological heritage protection. This growing interest can be seen from the Ramsar Convention on Wetlands and the Geosites project initiated by the IUGS (International Union of Geological Sciences) Global Geosites Working Group supported by UNESCO as a specific form of Wold Heritage (Carbajal and González-Martínez, 2003; García-Cortés, A. *et al*., 2001; González-Martínez, 2003; Röhling and Schmidt-Thomé, 2004)

Figure 27: Special Conservation Area of the *Juslibol* Oxbow located in the proximity of *Juslibol* on the north-west of Zaragoza city. May 2004.

3.1.8. Geo-hazards

The city of Zaragoza is located in a covered gypsum karst area where the different Quaternary deposits (terraces and glacis) directly lie on the Tertiary evaporates (see chapter 5.2.1. for the process description). It is well known that gypsum can be dissolved faster than limestone. The rate of gypsum dissolution in water is approximately 30-70 (Klimchouk *et al*., 1996) to 100-150 (Martínez *et al*., 1998) times higher than that of limestone. According to Ford and Williams (1989) solubility of gypsum at pH 7 is 2400 mg/l while calcite has a solubily between 100 and 500 mg/l. Thus, karstification processes are especially intense in this covered evaporite karst areas, although the supply of water by annual precipitation in this semiarid environment is less than 350 mm.

Four conditions must be present for evaporite karstification to be considered active. These include (Johnson, 2005; Lamont-Blanck *et al*., 2002):

- An evaporite deposit in the subsurface.
- Water that is unsatured with respect to the evaporite mineral.
- An outlet for the escape of solvent water.

- Energy to cause water to flow through the system.

In the study area these conditions are met. Karstification has been active throughout the Quaternary, producing dolines which correspond to collapse (sinkholes) or subsidence dolines with a wide range of sizes.

Some human-induced factors are irrigation, breaks in water supply network and pumping, which produce seasonal variations of the water table involving rapid changes in hydraulic gradients which, in turn, are considered as a factor favouring solution and piping. In the last decades, the subsidence and doline development in this area led to enormous economic losses, caused by rupture of irrigation infrastructures (Figure 28, 29) and water supply networks, as well as the destruction of transport infrastructures and buildings (Figure 30). The total economic losses due to all these factors are estimated to be of the order of tens of million of dollars (Soriano and Simón, 1995).

Most of the studies performed in relation with doline development in this area are oriented to solve punctual problems, but many experts agree with the necessity of a regional analysis of this phenomenon for urban planning (Benito *et al*., 2000; Guerrero *et al*., 2004; Gutiérrez-Elorza and Gutiérrez-Santolalla, 1998; Simón *et al*., 1998a; Simón *et al*., 1998b; Simón and Soriano, 2002), which is especially necessary in complex areas characterized by a dynamic industrial and urban development and an intensive agricultural use, as in the case of Zaragoza surroundings.

According to Paukštys *et al*. (1999), the most cost-effective way of planning in these areas lies in avoiding the existing dolines and most subsidence prone areas. The application of this preventive philosophy requires the recognition of the areas affected by subsidence and the production of hazard maps (Guerrero *et al*., 2004).

Another important geo-hazard in the region is erosion. In addition to natural factors, as a consequence of land-use changes, erosion processes may also cause severe damage in the study area. The erosion process on slopes implies the detachment and transport of the soil particles. The required energy for this process is supplied by rain drop impact, superficial flow and combination of both phenomena (Gutiérrez-Elorza and Sancho, 1993). Soil particle size and distribution, soil structure and stability are the main soil properties responsible for susceptibility to erosion in arid regions. A semiarid climate and rainfall distribution predominated by storm events further exacerbate the risk of soil loss.

Moreover, because of the solubility of gypsum, soil erosion can adversely affect water quality as the eroded material is transported by superficial flows, increasing their salinity and conductivity. From an ecological point of view, both desertification and salinization are serious concerns in Zaragoza Province (Machín and Navas, 1998). Limiting edaphic and climatic conditions, predominant in this province, in conjunction with poor land management, overgrazing and deforestation pose a serious problem for both surface water quality and soil, as the latter is a non-renewable resource in the area.

Figure 28: Doline developed in an old section of the *Canal Imperial de Aragón* canal at the south of *El Burgo de Ebro*. May 2004.

Figure 29: Breakdown in a small canal on the proximity of *La Cartuja* due to slow subsidence of the terrain. March 2006.

Figure 30: Presence of cracks in the floor and walls on the parking lot of a factory in the west of Zaragoza city. Photo by Andreas Deckelman and Christian Tigler. February 2006.

Gullies present the most conspicuous erosion forms in the Mediterranean Region. Incising the Quaternary sediments of many valley bottoms, they frequently threaten agricultural fields and plantations. In Spain, gullies (span. *barrancos*) are considered as the main sediment source responsible for a rapid siltation of reservoirs, which are of vital importance for supply with drinking and irrigation water (Marzolff, 1999; Marzolff *et al*., 2003; Ries and Marzolff, 2003).

The Quaternary deposits of the Ebro Depression in the study area form an unconfined alluvial aquifer with a high hydraulic conductivity and low thickness of unsaturated materials (Bielza de Ory and Martínez-Gil, 1994; Martínez-Gil, 1995; Octavio de Toledo, 1986; Octavio de Toledo and Arqued, 1990; Sahuquillo, 1976; Sánchez-Navarro et al., 2004). This fact implies that the groundwater is highly vulnerable to water-contaminant substances, which in turn, implies consequences for land-use decisions and the risk management of existing industrial facilities.

The volume of water extraction from the Ebro alluvial deposits in the area between *Luceni* (38 km upstream Zaragoza) and Zarazoza is about 40 hm^3 per year. However, this high amount represents only 25 % of the potentially extractable water (Bielza de Ory and Martínez-Gil, 1994). On the other hand, aquifer contamination is an irreversible process, unless high cost recovering practices are performed. Thus, a decrease in groundwater quality may reduce available quantities or may even hinder a yield. In the last decades, the intense irrigation and the use of pesticides is threatening the quality of the groundwater and, as a consequence, the amount of usable groundwater at a reasonable cost.

Floods and landslides also play a role in the study area, although they are of less economical and environmental impact. Though the central sector of the Ebro River presents a meandering pattern prone to flooding. However continuous modification of the river banks, the ongoing regulation of this river, especially the construction of several reservoirs and dams, has produced a decrease in the number and magnitude of floods in the last decades (Ollero, 1996). Despite these efforts, there was a great flood in the Ebro River in February 2006 reaching up to 3000 m^3/s in Zaragoza, which covered a great surface of terrain (Figure 31).

The geometry of the fluvial valley in the area is assymetric, with prominent gypsum scarps along the left bank. These gypsum scarps are affected by numerous landslides (Figure 32). These slope movements may be hazardous, may dam rivers and cause flood of the alluvial plains. As to the destruction of buildings and infrastructures in the study area, this is a problem only for a few houses in two villages (*Alfocea and Juslibol*) which are located in close proximity to the scarps, to the north-west of Zaragoza (personal communication Alfredo Ollero).

Figure 31: Flood mapping over a false colour composition of satellite image (SPOT 5, 10/2/03). Source: slightly modified after Losada *et al*. (2004).

Figure 32: Landslide in the gypsum scarp near *Alfajarín* village. Photo by José Luis Peña-Monné. July 1992.

3.2. Human environment

As mentioned above, Zaragoza city is located inside the homonym area in the region *Corredor del Ebro*, a highly dynamic economic axis and densely populated area within the Iberian Peninsula. The strategic position of this city, between four of the most developing areas in the Iberian Peninsula (*Madrid, Barcelona, País Vasco* and *Valencia*), the confluence of three rivers and the existence of many resources, in particular water, which is widely known to be a driving force for economic development, caused a population increase in the city of Zaragoza. This concentration and, as a result, increase in population has been a continuing process along the whole 20th century, and it is still in progress at present.

Some of the most remarkable points in the History of this demographic and economic evolution were, first of all, the declaration of Zaragoza in 1964 as Focus of Industrial Development, and, secondly, the settlement of General Motors Spain (GMS) in the municipality of *Figueruelas* in 1979, located 30 km upstream of Zaragoza. At present, population growth and economic development in the city have been given a new impulse after the city was appointed as venue for the 2008 International Exposition on the subject “Water and Sustainable Development” in 2004.

However, not only Zaragoza will be affected by this dynamic demographic and economic development, but also the 23 municipalities which comprise the study area and, in many cases, this increase is even greater than in Zaragoza. Map 4 shows the distribution of the municipalities in the study area. Table 1 shows the population of every municipality according to the ten years periodicity population census in

1900,1960, 1981, 1991 2001 and 2005, according to the last annual census revision. All the information related to population can be easily obtained from the web page of the Aragon Institute of Statistics (IAE, *Instituto Aragonés de Estadística*), included in the Aragon Government web page (**http://www.aragob.es**).

Table 1: Population recorded in the municipalities since 1900, according to the Population Census of *Instituto Aragonés de Estadística*.

Municipality	1900	1960	1981	1991	2001	2005
Alagón	3,454	5,334	5,086	5,522	5,620	6,187
Alfajarín	910	1,188	1,283	1,458	1,548	1,816
Bárboles	640	740	423	355	315	310
Botorrita	351	479	385	465	482	481
Burgo de Ebro (El)	903	1,186	1,171	1,223	1,628	1,894
Cabañas de Ebro	493	744	607	561	544	519
Cadrete	647	665	680	917	1,784	2,303
Cuarte de Huerva	275	491	1,148	1,353	1,922	3,078
Figueruelas	367	672	705	870	1,058	1,133
Fuentes de Ebro	2,221	3,337	3,670	3,801	3,887	4,086
Grisén	360	708	501	485	470	484
Joyosa (La)	264	485	357	345	430	697
María de Huerva	581	698	734	810	1,531	2,498
Muela (La)	729	1,011	852	1,006	1,773	3,265
Nuez de Ebro	455	538	481	526	581	646
Pastriz	707	929	775	752	1,083	1,259
Pinseque	750	1,356	1,178	1,363	1,819	2,479
Puebla de Alfindén	985	1,287	1,383	1,463	2,296	3,559
Sobradiel	421	684	582	598	708	813
Torres de Berrellén	1,136	1,808	1,528	1,436	1,374	1,430
Utebo	1,382	3,289	5,673	7,671	11,896	14,037
Villafranca de Ebro	663	726	725	670	677	734
Zaragoza	98,125	303,975	571,855	594,394	614,905	647,373
Total	116,819	332,330	601,782	628,044	658,331	701,081

The selection of these dates is due to the existence of four distinct periods in the population growth, as can be clearly observed in Figures 33, 34 and 35. These periods are evidently influenced by the economic evolution of the area; these are:

- Period 1900-1960: characterised by the predominant primary sector devoted to agricultural and farming activities, with a constant and slow growth of population in all the municipalities and a small period of decrease around the years of the Civil War.

- Period 1960-1981: characterised also by a general increase of population due to the declaration of Zaragoza as Focus of Industrial Development and the generalized rural exodus of population in favour of the capital cities, which was a general feature of these decades in the whole country. Thus, this increase is concentrated in the city of Zaragoza. The municipalities in the surroundings maintain, or even loose, a little of their population.

- Period 1981-1991: influenced by the establishment of GMS in *Figueruelas*, which determined the growth of municipalities with a good communication between GMS and Zaragoza (*Utebo, Pinseque*). Besides this, the population also grew in other nuclei with developing industrial areas (*Cuarte de Huerva* and *Cadrete*, in the *Huerva* corridor, and *Alfajarín* and *La Puebla de Alfindén*, downstream of Zaragoza). Zaragoza decreases its growth rhythm in favour of the surrounding areas due to the search, by its inhabitants, for more open spaces and the proximity to the natural environment. The nuclei with more rural characteristics, still devoted to agricultural activities and with no industrial development, such as *Cabañas de Ebro, Báboles, Grisén, La Joyosa* and *Pastriz*, even experienced a decrease in population.

- Period 1991-2005: characterised by a definitive increase in activities of the tertiary and construction sectors and extremely influenced by the settlement of the International Exposition in Zaragoza. There is a remarkable increase in size of Zaragoza, but this increase is not materialised in an increase in population. The extremely high cost of housing inside the city results in a movement of population to the peripheral areas. This influences the maximum increase of population of the municipalities in the study area of the last century.

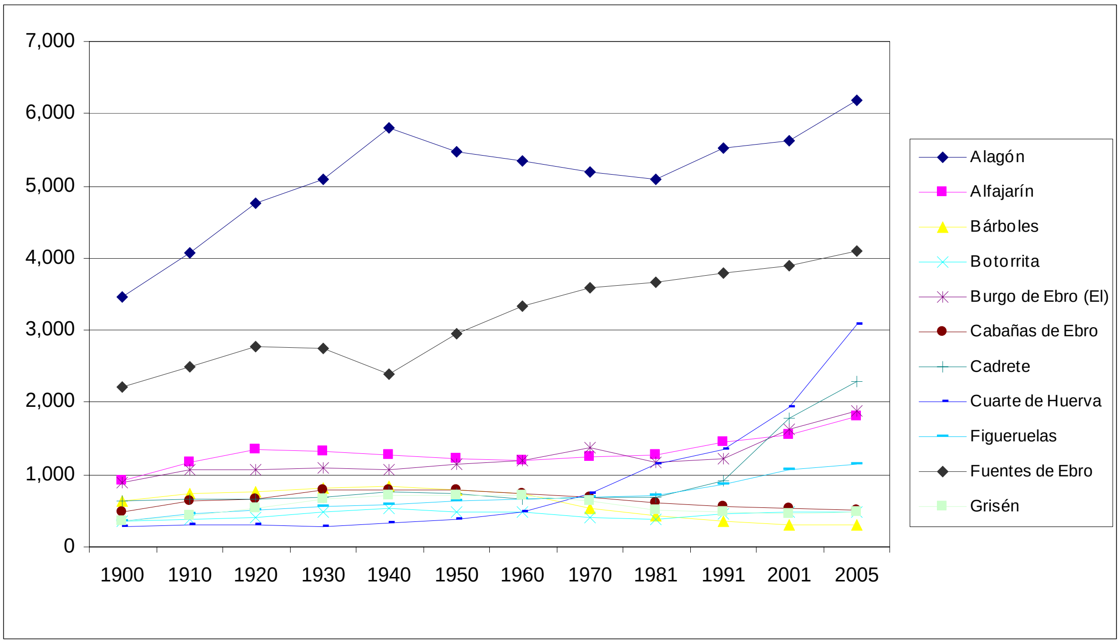


Figure 33: Population evolution along the 20th century till 2005. *Alagón, Alfajarín, Bárboles, Botorrita, El Burgo de Ebro, Cabañas de Ebro, Cadrete, Cuarte de Huerva, Figueruelas, Fuentes de Ebro, Grisén*. Source: *Instituto Aragonés de Estadística*.

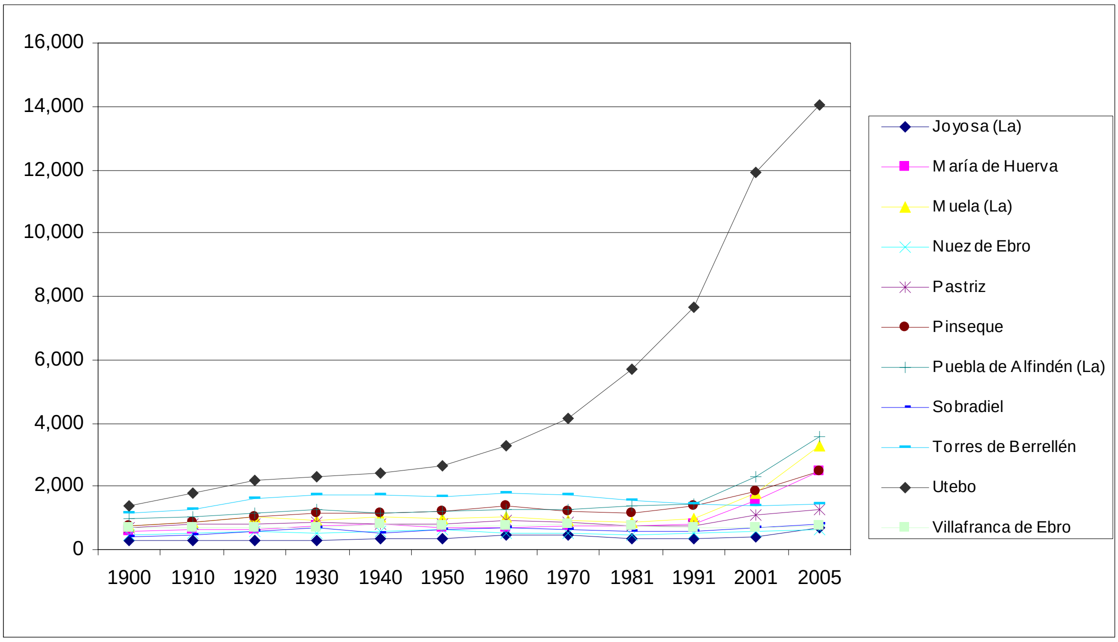


Figure 34: Population growth throughout the 20th century untill 2005. *La Joyosa, María de Huerva, LaMuela, Nuez de Ebro, Pastriz, Pinseque, La Puebla de Alfindén, Sobradiel, Torres de Berrellén, Utebo, Villafranca de Ebro*. Source: *Instituto Aragonés de Estadística.*

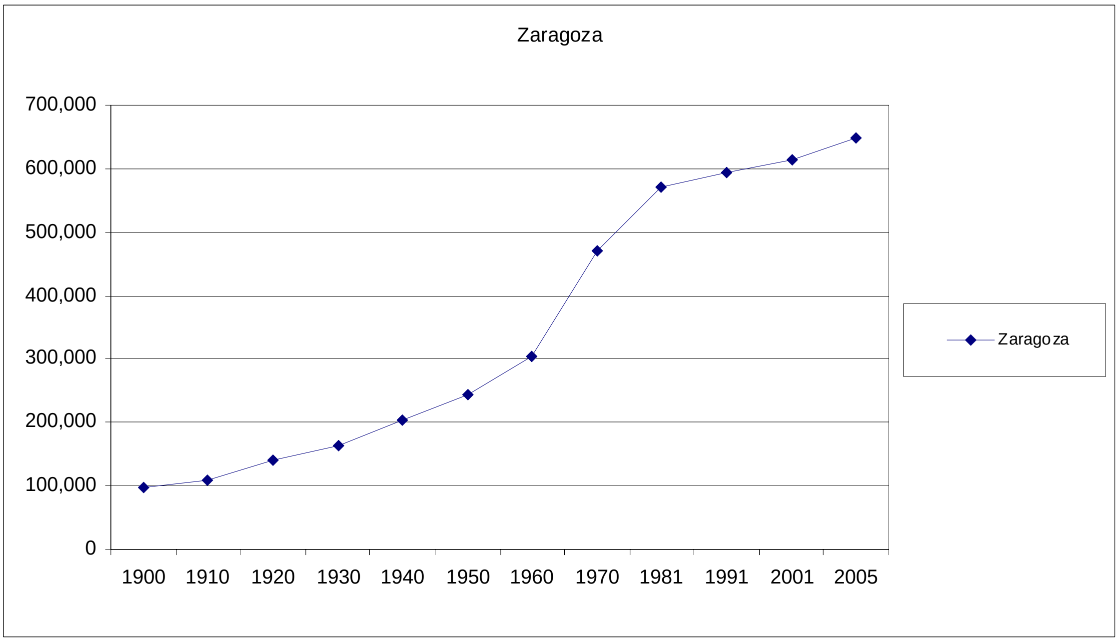


Figure 35: Zaragoza population evolution along the 20th century till 2005. Source: *Instituto Aragonés de Estadística*.

The total population located in the study area, according to the last annual census in 2005, is 701.081 inhabitants, although it is important to stress that not all the main urban nuclei of the municipalities are located inside the boundaries of the study area, such as *Fuentes de Ebro* and *La Muela*. It is also important to stress the extremely high increase in population of *Utebo*, probably due to its location in the Ebro Corridor upstream of Zaragoza, between the mentioned city and GMS and relatively close proximity to the capital, but also due to the establishment of one of the first commercial centres, *Alcampo*, in this study area.

Table 2 shows the total active population of every municipality by sectors of activity, according to the last ten year periodicity census in 2001. As mentioned above, the Tertiary Sector plays an important role at present, although industry is still an important sector, with percentages between 20 and 55 of the total active population, which in some cases, as *Figueruelas*, are even greater than services.

The historical demographic and economic evolution of Zaragoza has obviously determined the evolution in land use and, as a consequence, in land cover. The abandonment of agricultural activity in many municipalities in favour of industry resulted in the consequent abandonment of agricultural land. The industrialization caused a first concentration of population and activities in the city that later on would move to the surrounding areas, determining the existence of a mixed land use: rural, industrial, residential and tertiary. This situation caused land-use conflicts, due to the velocity of the space colonization process. In some cases the negative interactions with the geosphere were ignored during the fast urban development.

Table 2: Distribution of active population in sectors, according to the last population census of ten year periodicity, in 2001. Source*: Instituto Aragonés de Estadística*.

Municipality	Active population	Agriculture %	Industry %	Construction %	Services %
Alagón	2,400	5	36	10	49
Alfajarín	727	5	33	9	54
Bárboles	123	27	33	6	34
Botorrita	193	7	27	9	57
Burgo de Ebro (El)	755	6	30	11	54
Cabañas de Ebro	211	9	53	7	31
Cadrete	873	5	30	9	55
Cuarte de Huerva	945	2	34	10	54
Figueruelas	474	4	54	6	36
Fuentes de Ebro	1,693	15	36	16	33
Grisén	190	4	44	9	43
Joyosa (La)	181	14	33	7	46
María de Huerva	726	4	25	6	64
Muela (La)	840	5	22	11	62
Nuez de Ebro	273	11	31	10	48
Pastriz	489	4	26	11	58
Pinseque	835	9	33	8	50
Puebla de Alfindén	1,156	4	36	7	53
Sobradiel	273	4	34	7	55
Torres de Berrellén	561	8	37	11	45
Utebo	5,641	3	35	9	53
Villafranca de Ebro	280	8	28	5	59
Zaragoza	261,857	1	23	8	68
Total	281,696	1	24	8	67

At present, although much agricultural land has been abandoned, this activity still uses the majority of surface in the study area. Table 3 presents the land cover distribution of the 23 municipalities of the study area, according to the 1T statistics from the Aragon Government in 2001 (available at **http://www.aragob.es**). Agricultural land, grassland and forestry occupy more than half of the surface: about 106,000 ha. Also noteworthy is the large percentage of the 81,674 ha dedicated to agriculture land, namely 32,755 ha, is irrigated land. The main part of this irrigated land is used for growing corn, lucerne, wheat, tomatoes and fruit trees, such as apple, peach and pear trees. Wheat and almond tree occupy most of the dry land surface.

A good review of the industrial evolution of Zaragoza may be found in Hormigón (1999). Nowadays, according to the information supported by the Aragon Institute of Public Works (IAF, *Instituto Aragones de Fomento*), the total area dedicated to industrial uses is about 4,400 ha. A total of 83 industrial areas, distributed along the Ebro and *Huerva* Valleys and the main transport axis, are localized in the study area, (see Map 48). The general information about industrial areas for the whole Aragon Region can be easily downloaded from the IAF web page (**http://www.iaf.es**).

Table 3: Land cover distribution in the 23 municipalities of the study area, according to the 1T statistics from the Aragon Government.

Land cover	Dry land (ha)	Irrigation (ha)	Total (ha)
A.- Agricultural land	48,919	32,755	81,674
B.- Grassland	19,330	0	19,330
C.- Forestry	5,467	140	5,607
D.- Other	87,523	0	87,523
A + B + C + D	161,239	32,895	194,134

UGT Aragón *et al*. (2001) produced a revision of the main industrial areas in Zaragoza surroundings. They studied the actual situation of 23 of these areas. Although the number of industrial sites included in the study is low, their results are representative enough of our study area to be described here. The main activities developed in the industrial sites are commerce and distribution, with 30% of the total activities, followed by metal industry (20,8%), transports and communications (9.8%), services (5,9%) and electricity (5,6%).

Map 5 shows the land cover of the study area, according to the CORINE (Coordination of information on the Environment) land cover cartography reviewed by the Aragon Government in 2000. The hectares occupied by the different land covers can be seen in Table 4. This information is more accurate for the study area than the 1T statistics, since the latter is referred to the entire municipality, and the CORINE (Coordination of information on the Environment) information refers only to the study area. Approximately, 29% of the 89,829 ha that comprise the study area is irrigated land. It is followed by scarcely vegetated areas of sclerophyllous vegetation (18%), agricultural dry land (16%) and agricultural dry land mixed with areas of natural vegetation (7%).

Table 4: Distribution in hectares of the land cover in the study area, according to the CORINE (Coordination of information on the Environment) land cover cartography, revised by the Aragon Government in 2000.

Land cover	area (ha)
Airports	821
Construction sites	1,380
Continuous urban fabric	2,687
Discontinuous urban fabric	2,076
Dump sites	256
Green urban areas	155
Industrial or commercial units	2,656
Mineral extraction sites	394
Road and rail networks and associated land	1,410
Sport and leisure facilities	344
Agricultural land with areas of natural vegetation	7,061
Fruit trees and berry plantations	469
Non-irrigated arable land	16,144
Olive groves	77
Broad-leaved forest	1,625
Complex cultivation	2,026
Coniferous forest	1,024
Inland marshes	32
Permanently irrigated land	29,192
Natural grassland	452
Sparcely vegetated areas	17,842
Transitional woodland shrub	422
Reservoir	4
Water courses	1,281
Total	89,829

4. Geo-resources mapping

4.1. Sand and gravel deposits

Zaragoza City is crossed by the Ebro River, the most plentiful river within the Iberian Peninsula, the *Gállego* River and the *Huerva* River. The terraces of these three rivers and the *Jalón* River, tributary of the Ebro on the right bank, represent a valuable geo-resource in terms of sand and gravel deposits.

According to the Geological map from the ITGE, eight levels of terraces are recognized in the study area (Map 2). As has been mentioned above, terrace levels T4, T5, T6 and T7 are relatively important for sand and gravel extraction, due to their extension and the characteristics of the materials.

Terrace T4 was deposited during the Upper Pleistocene. This terrace occupies a wide area of terrain, parallel to the Ebro River bed on the right bank, of about 2,5 km width and 20 km length. The estimated thickness is 15 m. It consists of sandstones and quartz gravels with diameters between 2 and 10 cm in a sandy matrix. In the upper part of the profile sometimes a calcareous crust appears (called *mallacán* in the region), which should be eliminated for extraction purposes (Manso *et al*., 2001).

Terrace T5 was deposited during the Middle Pleistocene. The composition of this terrace is similar to T4. The estimated thickness is between 20 and 25 m. The superficial extension of this terrace is much less than T4, about 7 km^2.

Terraces T6 and T7 were deposited during the Low Pleistocene. Terrace T7 is only present in the area downstream Zaragoza and occupies an area of about 6 km^2. T6 is more disseminated in the study area, especially downstream Zaragoza.

The low value on the market of this resource determines the local characteristic of this activity, since long distance transport of this resource is not viable. The total amount of resource in the municipality of Zaragoza is quantified in 3,012 million of tons (Manso *et al*., 2001). The geographical distribution of the different percentage is: 60.2% (1,814 Mt) in the Ebro Basin, 39.5% (1,191 Mt) in the *Gállego* Basin (mainly outside the study area) and 0.2% (7 Mt) in the *Huerva* Basin.

As mentioned in chapter 2.3.3.4, for the location and mapping of this resource in the surroundings of Zaragoza, Oswald Marinoni developed a geological 3D model of the Quaternary deposits existent in the study area within Gocad. Thus the information in this chapter has been taken from a submitted publication (Lamelas *et al.*, 2006b). The relevant passages extracted written by Oswald Marinoni are marked with quotation.

This model was created using information from more than 900 boreholes (including the *Gállego* area). The majority of the boreholes are located in the Ebro

Valley (Map 6). This information was obtained from the IPA of the Ebro Basin Authority (CHE) and completed with several borehole data collected from different private enterprises (Control-7, Entecsa, Z-amaltea, CTA, ESHYG) and from previous studies carried out for the construction of several roads (M.O.P., 1967, 1970, 1973, 1994, 2000, 2003). The collection of new data was very important, as there were very few boreholes, which penetrated the Tertiary under the Quaternary in the IPA.

The boundary of the area covered by the geological 3D model is based on the underlying geoscientific problems, such as doline development and groundwater vulnerability models, for which this model will be also needed. For these reasons, the construction of the 3D model is reduced to the greyed area of Map 6 which comprises the Quaternary deposits of the Ebro Valley, the region's dominant aquifer, and the pediments. Nevertheless, it should be noted that the accuracy of the model is determined by the limited information available concerning the Ebro Alluvial deposits downstream *La Cartuja* and pediments located in the right back of the Ebro River upstream Zaragoza.

According to Lamelas *et al.* (2006b) "The geological information taken from the available boreholes was processed in the following way:

- Structured data storage in a database.
- Evaluation of borehole data. Therefore the boreholes were scanned with regard to lacking, imprecise or fragmentary information on the lithology. These boreholes were removed. Since the construction of the 3D model was limited to the Ebro Valley, boreholes located on the gypsum platforms were also removed.
- Many boreholes were drilled for small civil engineering projects and, therefore, do not reach great depths and the Tertiary respectively. Most of the boreholes with a depth smaller than 5 m were removed for that reason, since they did not provide information on the Quaternary-Tertiary boundary. However, boreholes were not removed without checking their position in the valley and their lithological information. After the cleaning of the borehole database, approximately 500 boreholes remained in the data pool.
- Definition of more than 20 cross-section lines approximately perpendicular to the strike of the Ebro Valley (Map 7 and Attach 1). Three cross-sections were defined parallel to the strike of the valley. As a means of visual support, the information of the boreholes being nearest to a cross-section line was plotted.
- Systemisation of the borehole lithology by help of the cross-sections. The encountered layers were coded as either Quaternary or Tertiary.

Tertiary was definitely reached when gypsum was encountered. However, gypsum was not reached in every borehole. In these cases the information of the Geological map, the cross-sections and expert knowledge of the local geology was combined. In case that a clear assignment was not possible a borehole remained uncoded. On the whole, about 300 boreholes were identified to have reached the Tertiary in the Ebro Valley (Map 7).

- The tops of the encountered Tertiary surface were imported into Gocad as points distributed in a three dimensional space and then combined to a surface.
- Due to the subsidence phenomena, the region is well known for its anomalies of Quaternary thickness. Therefore, the database was again scanned for boreholes which have not reached the Tertiary, but show high apparent thickness of Quaternary. Since the mean value of the true Quaternary thickness was determined to be approximately 18 m, a borehole was integrated, if the apparent thickness was greater than 18 m. However, the definition of an anomaly is relative. An apparent thickness of 10 m might be considered an anomaly, if this location was surrounded by holes with true thickness of, say, 3 m. Therefore, the boreholes were always checked, also, for their position in space and the surrounding information. With this approach 92 boreholes were selected to "adjust" the existing surface of the top Tertiary (Figure 36). Even though this additional information must be regarded as not very precise, it helps approaching the reality" (Lamelas, *et al*., 2006b).

Figure 37 shows a perspective view of the final model of the top of the Tertiary inside the Ebro Valley (Quaternary layers have been removed). The 3D body between the terrain surface and the top Tertiary of the valley (Figure 38) will be filled with the lithological information of the boreholes which, in turn, will allow assessments with regard to the amount of available geo-resources like sand and gravel.

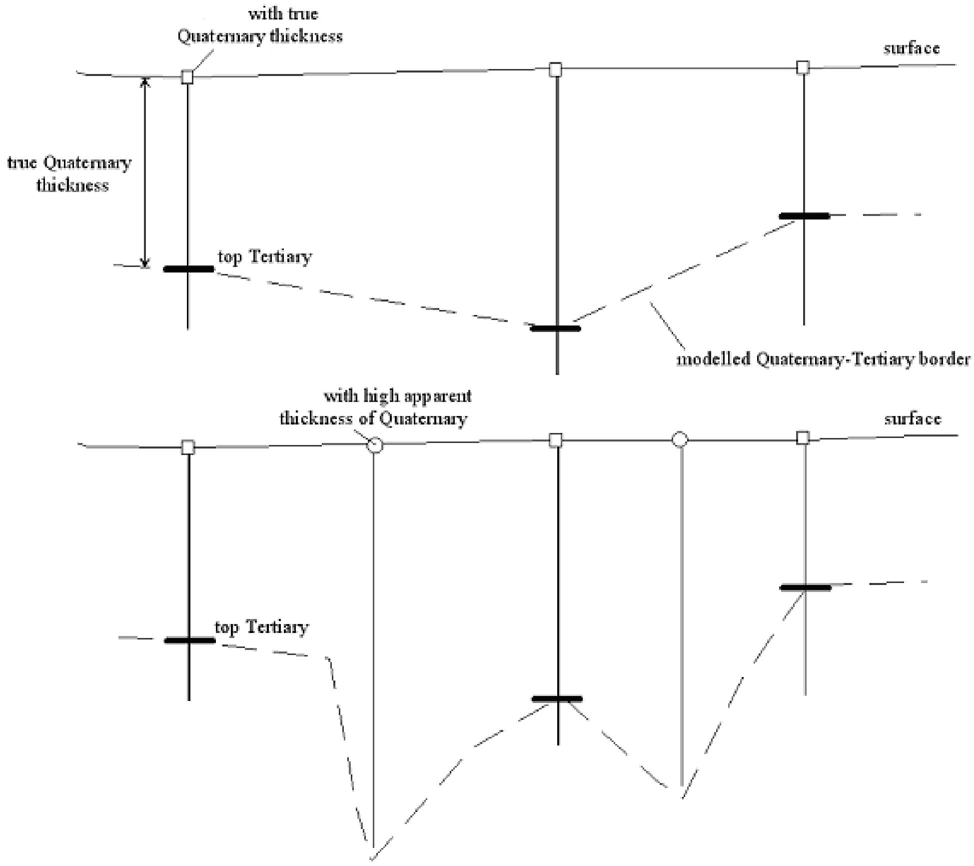


Figure 36: Principle of the "post processing" of the Tertiary top. Top: Modelling of the Tertiary border with drill cores where Tertiary was encountered. Bottom: Adjustment of the Tertiary top with high apparent Quaternary thickness. Slightly modified after Lamelas *et al,* 2006b.

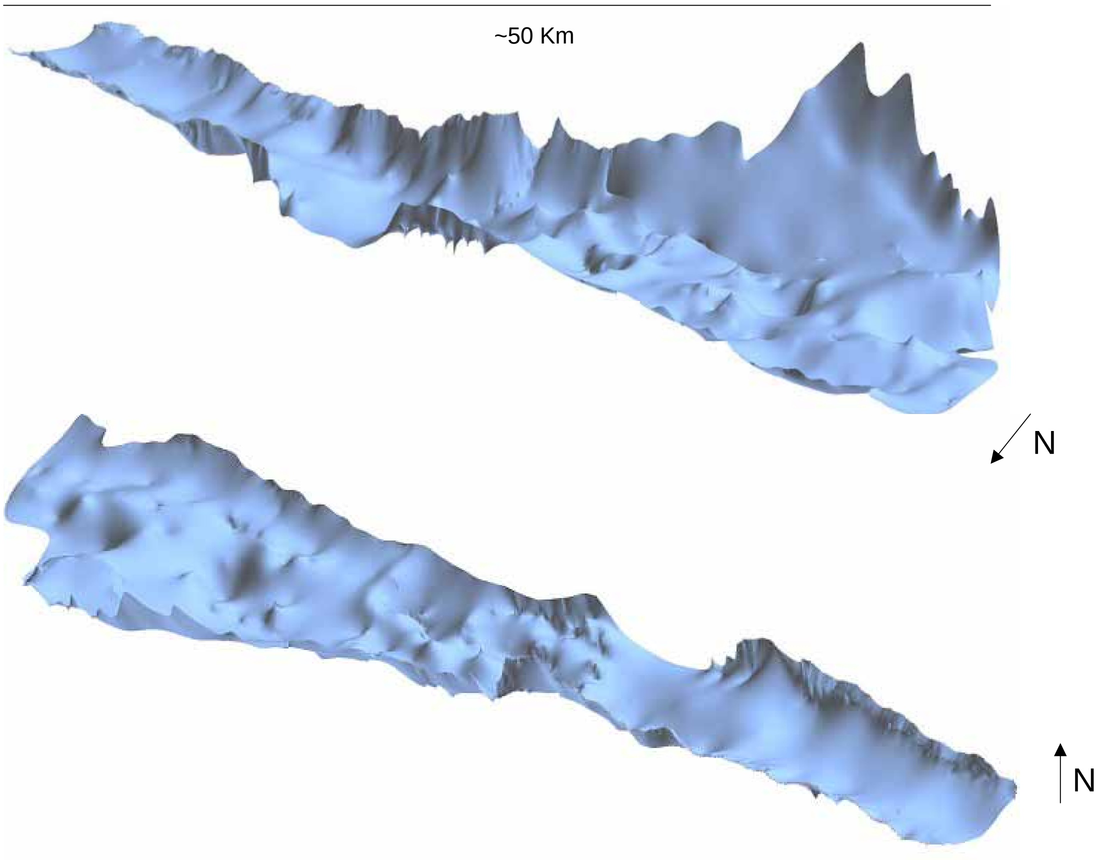


Figure 37: Top of the Tertiary in the study area (exaggeration factor 50). The Quaternary layers are removed.

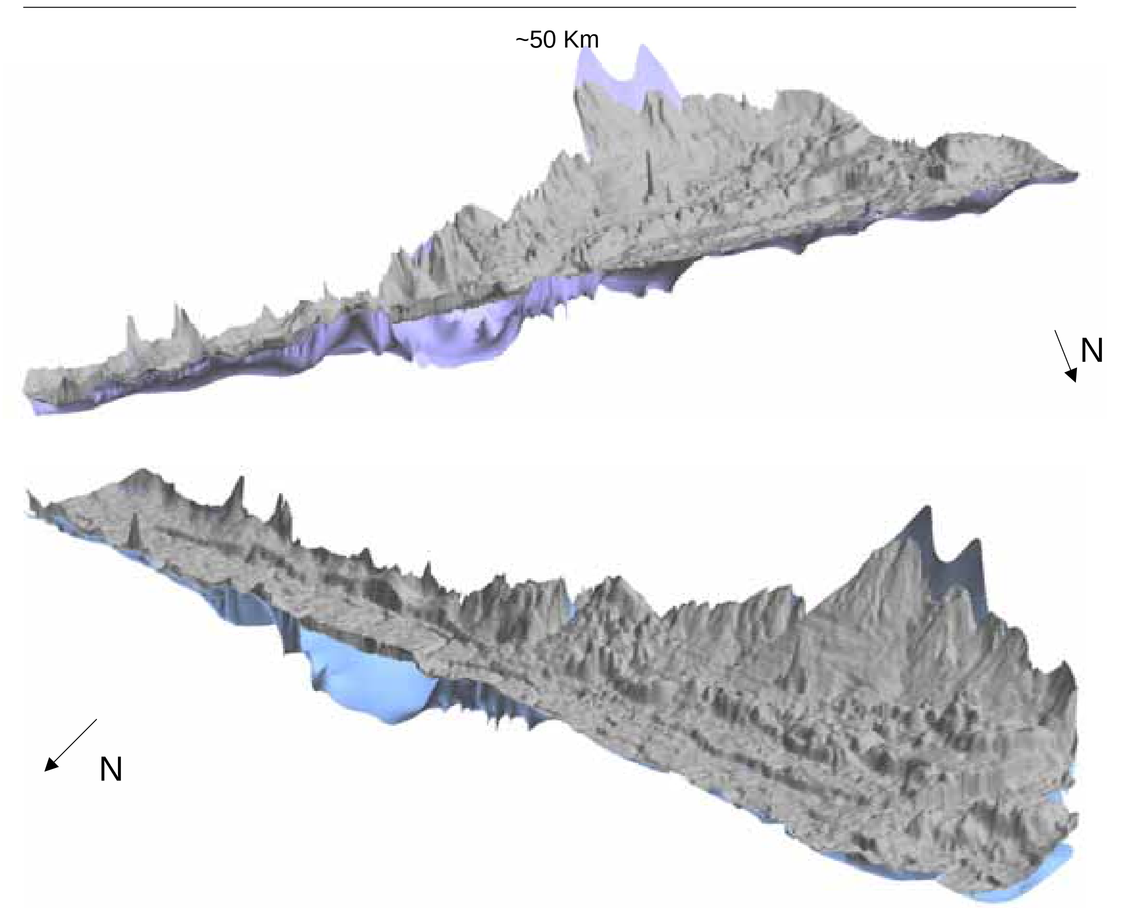


Figure 38: Quaternary surface above Tertiary layers surface (exaggeration factor 50).

To fill the space in between the upper and lower boundary, Gocad offers the sGrid object, which is a collection of initially regularly spaced cells which fill the three dimensions with information. However, a sGrid can be such deformed that it perfectly suits geometrical boundary conditions. Figure 39 shows an example of a regular sGrid and its deformation by geometric constraints. The deformed sGrid of the study area and a detail showing the irregularity of the grid can be observed in Figure 40. Please, note that all sGrid cells outside the study area were declared as nodata, thus indicating that they are to be excluded from further computations.

Next, the geological body was filled with information. The layers encountered in the boreholes were assigned with lithological information. These lithological values were then interpolated within the sGird object thus filling the 3D space. The interpolation method used was the discrete smooth interpolation algorithm (DSI) which belongs to the core functionality of Gocad.

Then, a script was applied to the sGrid, allowing a user defined computation of the cells containing data for sand and gravel and consequently the thickness of sand and gravel deposits (Figure 41). Afterwards, the information about sand and gravel thickness was projected as a point on a flat 2D surface. This collection of points was then imported by ArcGIS and transformed to a map of pixel size 100x100 m representing sand and gravel thickness. The same methodology was used for the creation of a model of overburden material thickness (Figure 41), that is, material located above the sand and gravel deposites, which cannot be used for construction purposes.

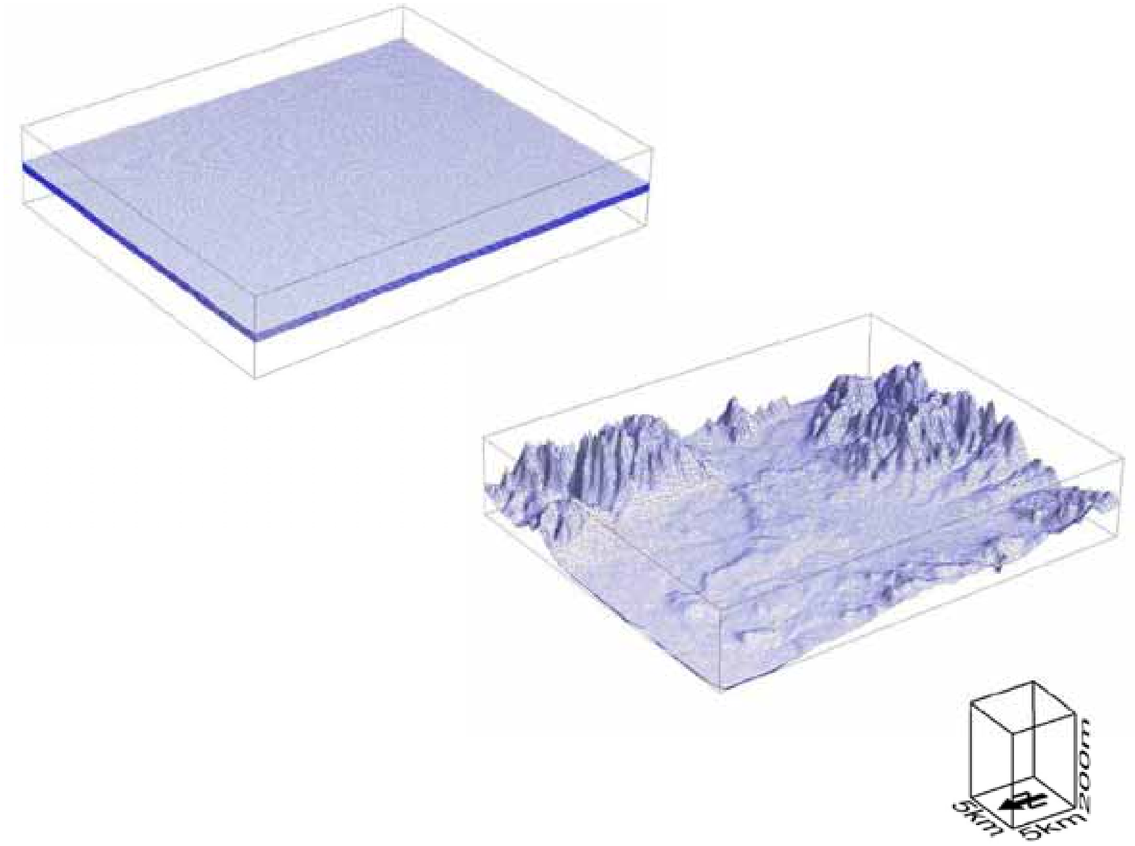


Figure 39: Gocad regular sGrid definition. a) regular sGrid before deformation, b) sGrid after deformation. After Lerch, 2005.

Maps 8 and 9 show both models. The maximum thickness of resource, more than 35 m is located in the T5, situated immediately south-west of Zaragoza, in some sectors of T4 upstream from Zaragoza, covered in many areas by glacis deposits making its exploitation more difficult, and in the contact between *Jalón* and Ebro Valleys. There is also great thickness in the contact between *Gállego* and Ebro Valleys in the north-east of Zaragoza. Important thicknesses of more than 20 m can be found surrounding these areas, and in the T6 level located upstream Zaragoza. High thickness of sand and gravel deposits are also present in the pediments upstream from Zaragoza, where the oldest alluvial terrace levels are presumably covered by the glacis. Nevertheless, due to the lack of information in this sector, it is difficult to decide whether these terrace levels have been eroded, previously to the pediment deposition, or still remain under them. Consequently, it is probable that the model gives an unrealistically high thickness in this sector.

The lowest thickness of sand and gravel deposits can be found in the proximity of the river bed, and also in areas matching with the sector where the maximum thickness of overburden is located for example, in the Ebro River flood plain north-west of *Pastriz* and south of *Nuez de Ebro*, and also in the Terraces T4 and T5 north-west of Zaragoza airport.

It is also important to stress the lack of borehole information downstream from Zaragoza, where the quality of the model is not as good as intended. However, this attempt to quantify the thickness of raw materials could be considered as a good step towards understanding the sand and gravel resources, in comparison to previous studies.

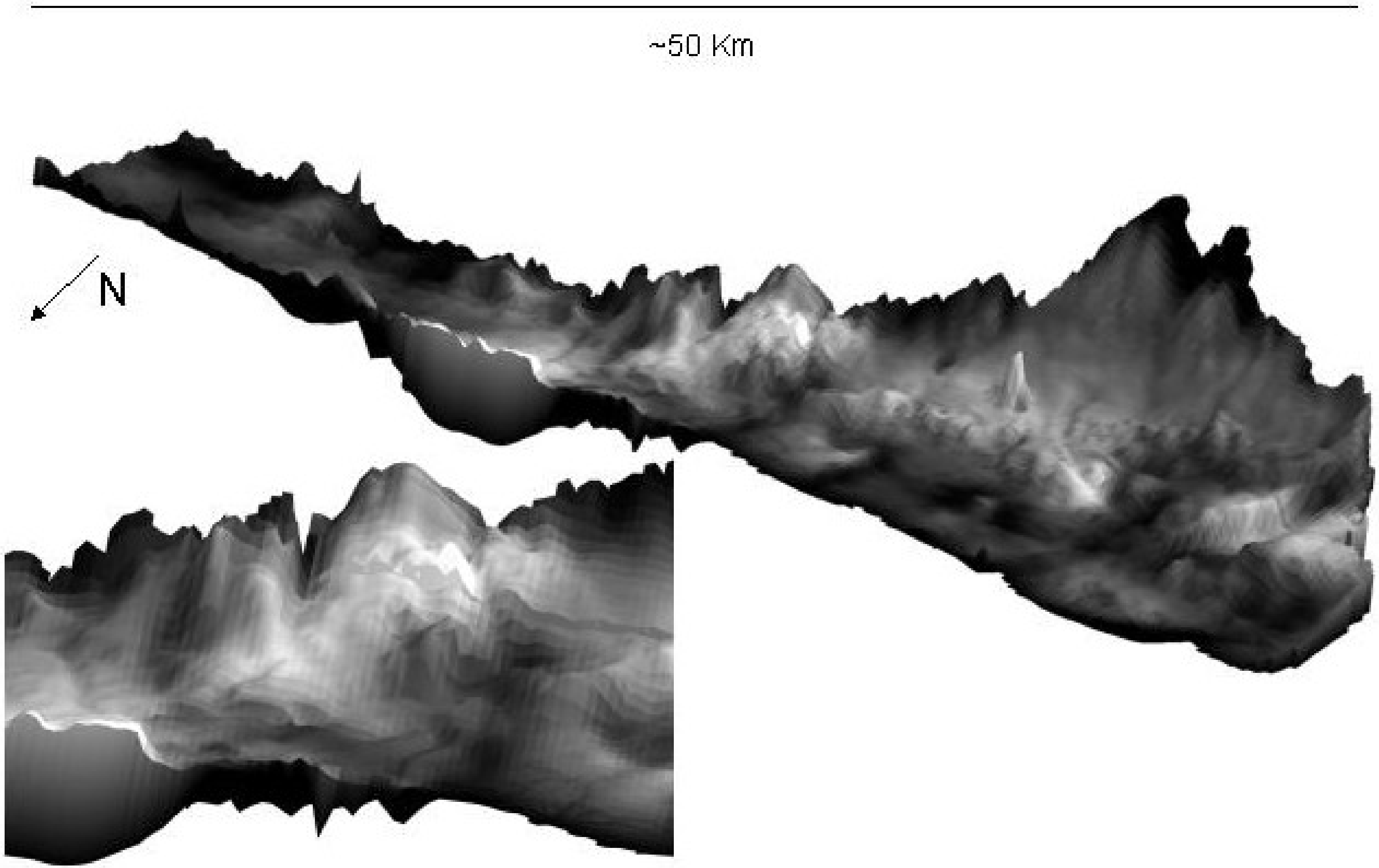


Figure 40: Deformed sGrid for the study area (vertical exaggeration factor: 50). In the detail can be observed the irregularity of the grid due to the deformation by geometric constraints.

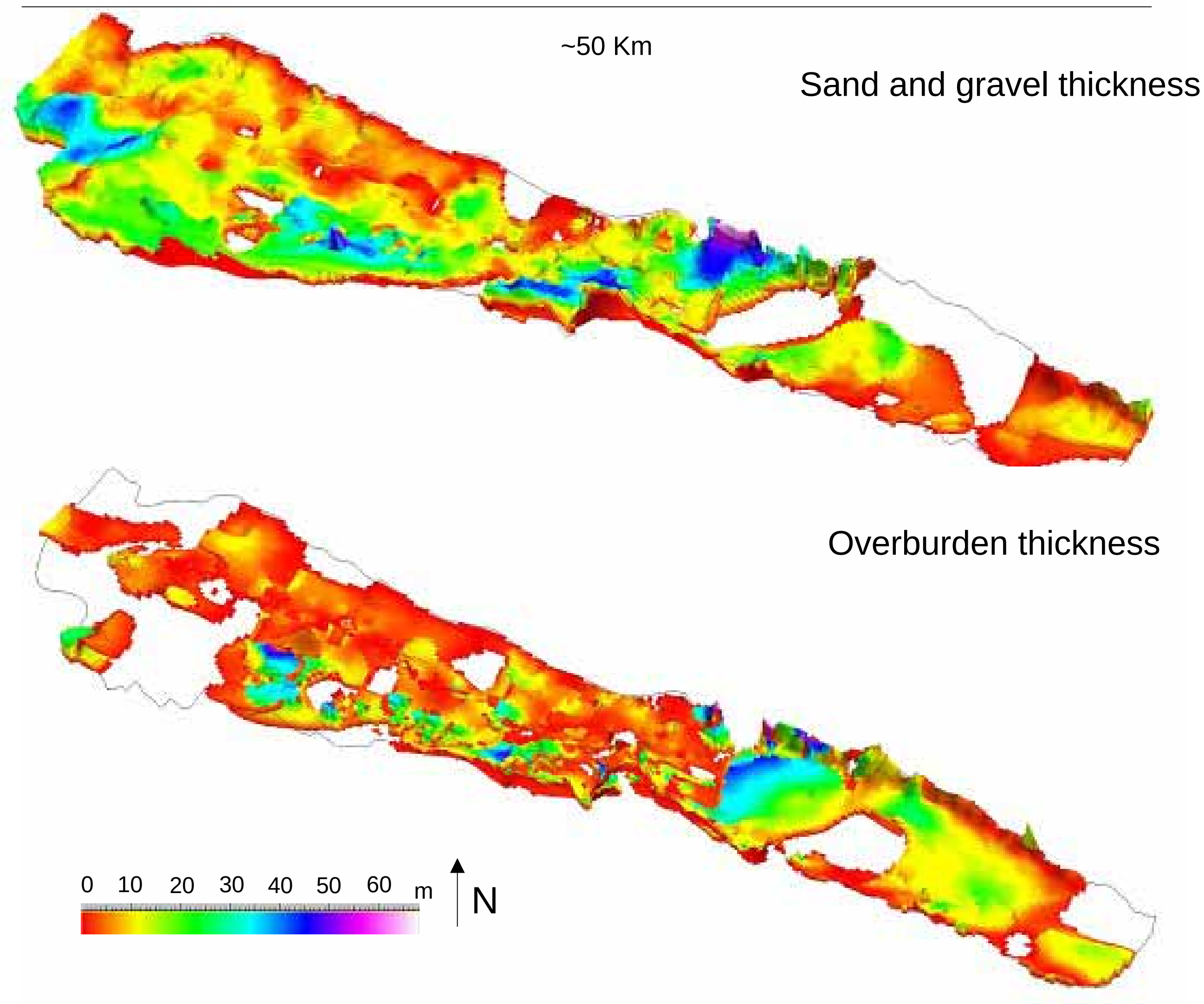


Figure 41: Sand and gravel thickness and overburden thickness three-dimentional model.

4.2. Natural areas under protection or worth protecting

As explained in the methodology, almost all natural areas with environmental and geoscientific value in the study area are protected by environmental law or land management plans. Thus, for the location of this resource, a simple cartography of these figures of protection and description is presented. Besides, other areas worth protecting not included in the mentioned laws were digitalized and added as areas that should be protected.

The areas included in the Natura Network 2000 include some of the protected spaces mapped here. This network includes Special Protection Areas (SPA) for birds, established by the Birds Directive (79/409/CEE), and Special Areas of Conservation (SAC) to be designated for other species, and for habitats, established by the Habitats Directive (92/43/CEE).

4.2.1. Habitats

Map 10 shows a cartography of the habitats present in the study area designeted and supported by the Aragon Government. In the next chapter includes a description of these habitats according to E.C.D.G.E. (1999).

4.2.1.1. Halophytic habitats

Salt and gypsum inland steppe environments, are represented by habitat 1520, “Iberian gypsum steppes of *Gypsophiletalia”* (Priority habitat). These are garrigues with gypsum-rich soils of the Iberian Peninsula, usually very open and a characteristic flora of numerous gypsophilous species. Characteristic syntaxa are *Lepidion subulati*, *Gypsophilion hispanicae*, *Thymo-Teucrion verticillati*.

4.2.1.2. Freshwater habitats

Represented by two different environments and three different habitats:

- Standing water environments, represented by habitat 3150, “Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition”*. These are lakes and ponds with mostly dirty grey to blue-green, more or less turbid waters, particularly rich in dissolved bases (pH usually > 7), with free-floating surface communities of the *Hydrocharition* or, in deep, open waters, with associations of large pondweeds (*Magnopotamion*).

- Running water environments, represented by habitat 3250, “Constantly flowing Mediterranean rivers with *Glaucium flavum”*, and 3280, “Constantly flowing Mediterranean rivers with *Paspalo-Agrostidion* species and hanging curtains of *Salix* and *Populus alba”.* The former are communities colonising gravel deposits of rivers with a Mediterranean, summer-low, flow regime, with formations of the *Glaucion flavi*. The latter are nitrophilous annual and perennial grass and sedge formations of the alluvial banks of large Mediterranean rivers, with *Paspalum paspaloides*, *P. vaginatum*, *Polypogon viridis* (=*Agristis semiverticillata*), *Cyperus fuscus*, and hanging curtains of *Salix spp.* and *Populus alba*.

4.2.1.3. Sclerophyllous scrub

Mediterranean arborescent matorral environments, represented by habitat 5210, "Arborescent matorral with *Juniperus spp",* are Mediterranean and sub-Mediterranean evergreen sclerophyllous scrubs organized around arborescent junipers. The subtype present in the study area is *Juniperus oxycedrus* arborescent matorral.

4.2.1.4. Natural and semi-natural grassland formations

These are also represented in the study area by two environments:

- Semi-natural dry grasslands and scrubland facies, represented by habitat 6220, "Pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea"* (Priority habitat). These are Meso- and thermo-Mediterranean xerophile, mostly open, short-grass annual grasslands rich in therophytes; therophyte communities of oligotrophic soils on base-rich, often calcareous substrates.

- Semi-natural tall-herb humid meadows, represented by habitat 6420, "Mediterranean tall humid herb grasslands of the *Molinion-holoschoenion"*. These are Mediterranean humid grasslands of tall grasses and rushes, widespread in the entire Mediterranean Basin, extending along the coasts of the Black Sea, in particular in dunal systems.

4.2.1.5. Forests

Mediterranean deciduous forests environments represented by habitat 92A0, "*Salix alba* and *Populus alba* galleries", and 92D0, "Southern riparian galleries and thickets (*Nerio-Tamaricetea* and *Securinegion tinctoriae*)". The former are riparian forests of the Mediterranean Basin dominated by *Salix alba* and *Salix fragilis*. Mediterranean and Central Eurasian multi-layered riverine forests with *Populus spp., Ulmus spp., Salix spp., Alnus spp., Acer spp., Tamarix spp.* and *Juglans regia*. Tall poplars, *Populus alba, Populus caspica* and *Populus euphratica (Populus diversifolia*), are usually dominant in height; they may be absent or sparse in some associations that are then dominated by species of the genera listed above. The latter are tamarisk, oleander, and chaste tree galleries and thickets and similar low ligneous formations of permanent or temporary streams, and wetlands of the thermo-Mediterranean zone and south-western Iberia, and of the most hygromorphic locations within the Saharo-Mediterranean and Saharo-Sindian zones.

4.2.2. Special Protection Areas (SPA) for birds

In the study area includes four SPAs (Map 11). These are:

- *Estepas de Belchite - El Planerón - La Lomaza*: this area of about 25,000 ha was created in 1999 and extended in 2002. In the study area, it has an extension of about 1,200 ha. It consists of a wide plain in continental Miocene materials, gypsum, drained in many places by several flat bottom valleys. It is a refuge of wild fauna and flora representative of the steppes in the Ebro Basin.

- *Galachos de la Alfranca de Pastriz, La Cartuja y El Burgo de Ebro*: this area of about 2,200 ha was declared SPA in 1993, and extended in 2002. It consists of abandoned meanders (oxbows or *galachos* in the local terminology) of the Ebro River in the central sector of the Ebro Basin. Riparian ecosystems where the thickets and wetlands have a great development and constitute an important colony of birds. It was previously declared as Natural Reserve in 1991.

- *Montes de Zuera, Castejón de Valdejasa y El Castellar*: area of about 25,542 ha created in 2000. It consists of the wide extension of the structural platform *Montes de Zuera y Castejón*, located in the left bank of the Ebro River, upstream the *Gállego* mouth. The dominant forest is composed of *Pinus halepensis* and the scrub of gypsophilous species. Important birds observed in the area are *Aquila chrysaetos, Milvus migrans, Neophron percnopterus, Bubo bubo* and *Gyps fluvus*.

- *Río Huerva y Las Planas*: they constitute an area of 30,326 ha that was also created in 2000. It consists of the structural platform reliefs and surrounding areas located on the right bank of the *Huerva* River, near its mouth. It presents a great diversity of vegetation, with important examples of gypsophilous scrubs and *Pinus halepensis* forest. The presence of species as *Aquila chrysaetos* and *Bubo bubo* is also important.

4.2.3. Special Areas of Conservation (SAC)

Five different SACs can be recognized. Map 11 indicates that, in many cases, these areas match with the SPAs. All these areas were proposed in 2000, with the exception of the *Galachos de La Alfranca, Pastriz, La Cartuja and El Burgo de Ebro*, which was proposed in 1998:

- *El Castellar*: this area of about 12,957 ha is only represented in the study area by the scarp of gypsum in the north-west of Zaragoza. This scarp possesses an accumulation of detritus at the bottom, in which a wide variety of flora has developed. The vegetation consists of gypsophilous scrubs with *Ononis tridentata, Gypsophila hispanica* and *Helianthemun squamatum.* Habitats existing in this area are 1520 and 5210.

- *Galachos de La Alfranca, Pastriz, La Cartuja y El Burgo de Ebro*: Oxbows in the Ebro River downstream Zaragoza, with an area of 804 ha, smaller than the SPA extension. Habitats present in the area are 3150, 3250, 3280, 6420, 92D0 and 92A0.

- *Montes de Alfajarín-Saso de Osera*: it consists of an area of 11,693 ha located in the left bank of the Ebro River downstream Zaragoza. This, as *El Castellar*, is only represented in the study area by the scarp of gypsum. This scarp also has an accumulation of detritus at the bottom, in which a wide variety of flora has developed. Habitats found in this area are 1520, 6220 and 92D2.

- Planas y estepas de la margen derecha del Ebro: these areas consist of 43,146 ha on the right bank of the Ebro River, between *Huerva* and *Martín* Rivers. In the study area, it is located in the slopes of the *La Plana* structural platform. The upper parts of the slopes are covered by forest of *Pinus halepensis* and the rest of the sector by sclerophyllous scrubs of *Rosmarinus officinalis, Quercus coccifera and Pistacea terebintus,* and gypsophillous scrubs with *Ononis tridentata, Gypsophila hispanica* and *Helianthemun squamatum.* In more degraded areas grasslands with *Brachypodium ramosum* and *Lygeum spartum* can be observed. Habitats present in this area are 1520, 5210, 6220 and 92D0.

- *Sotos y mejanas del Ebro*: these are small areas located along the Ebro River summing up to 1,853 ha. It consists of well preserved riparian areas and with a high biodiversity. The fluvial dynamic of the Ebro River is characterised by the development of meanders, due to the low slope of the terrain of between 0.4 and 1.2 m/km. The humid environment of the river banks and abandoned meanders makes the appearance of species typical for Atlantic environments possible. Habitats existing in this area are 3250, 3280, 6420, 92A0 and 92D0.

4.2.4. Natural protected areas

The Natural Reserve of *Los Galachos de La Alfranca, Pastriz, La Cartuja y El Burgo* is the only real natural protected area. It covers an area of about 777 ha, which almost matches the extension of the SAC (Map 12). Declared Natural Reserve in 1991 by the Spanish Law 5/1991, it was reclassified in 1998 by the Law 6/1998 of Natural Protected Areas (Figure 22). Inside this area there is a space included in the inventory of peculiar fluvial sites by the Aragon Government. This is a meander locally called *El*

Meandro del Rincón del Falso. This area is also an important refuge of birds as *Nycticorax nycticorax, Ardea cinerea, Anas crecca* and *Anas platyrhynchos.*

4.2.5. Natural resources management planning

Another type of protection has been recently approved for the environs of the Natural Reserve of the *galachos* and the Ebro River banks. This is the Natural Resources Management Planning of the thickets and oxbows of the Ebro River (PORN, *Plan de Ordenación de los Recursos Naturales*, *de los sotos y galachos del Ebro)*. This is a wide area between Zaragoza and *Escatrón* of about 39,700 ha. The aim of such planning is to support the management of areas and the fauna and flora species of great environmental value. The objective is to divide the space in different zones and to specify the land use permitted there (Map 12). This planning was approved initially in 2002 and provisionally in 2005 by the Aragon Government. It describes three different zones:

Zone 0: this is the area highest value in terms of conservation. This space is divided into two sub-zones. The sub-zone 0A matches exactly with the Natural Reserve *Los Galachos de la Alfranca, Pastriz, La Cartuja y El Burgo*, and the sub-zone 0B is the nearby area of the Natural Reserve upstream and downstream. It also includes another small area disconnected from the Natural Reserve a few meters downstream.

Zone 1: this comprises the Ebro River bed, the thickets, meanders and wetlands. For zone mapping, the limit of the area has is specified as the area located inside the ordinary flood water level. This area has a very high environmental value and must be preserved in order to maintain the continuity of river ecosystems since river banks are usually the preferred corridor for several migratory species.

Zone 2: the limit of this area is established at a distance of 500 m from Zone 1, but this area must be also included in the area of 500-year period of return of floods.

4.2.6. Geosites

As mentioned in chapter 3.1.7, in the last years, there has been an increasing international concern about the geological and geomorphological heritage protection. Since the definition of Geosites as a specific form of world Heritage by UNESCO many countries have developed an inventory of Geological sites (Carbajal and González-Martínez, 2003; García-Cortés *et al*., 2001; González-Martínez, 2003; Röhling and Schmidt-Thomé, 2004).

A comparatively high level of activities in the field of site management and exploitation of Geosites for educational and touristic purposes can be observed in Germany, where the Directors of the State Geological Surveys and the Federal Institute for Geosciences and Natural Resources (BGR) decided, in 1992, that the Geological Surveys should set up a working group to work out a concept for geotope conservation and created the *National GeoParks* in Germany, which were established as a follow-up to the German “Year of Geoscience”.

Geological sites (in Germany called Geotopes and Spanish Puntos de Interés Geológico) provide information on the evolution, structure and properties of the Earth's crust. They also contain the great variety of features that characterize a landscape and are commonly provide the habitat for endangered animals and plants. For this reason, their preservation is of special concern to geosciences and for the protection of threatened animal and plant species (Röhling and Schmidt-Thomé, 2004).

One of the responsibilities of a Geological Survey is to provide the scientific basis for selection and legal protection of sites for conservation. In this sense, The Spanish Geological Survey (IGME or ITGE) initiated the National Inventory of Sites of Geological Interest in 1977, in which all sites were given local, regional, national or international scope on the basis of their merits. Those responsible for the Geological Heritage at the Spanish Geological Survey considered it necessary to provide a list of geosites in Spain of international relevance for the world inventory promoted by the International Union of Geological Sciences. Thus a preliminary list of frameworks was drawn up by García-Cortés *et al*. (2001), forming the first Spanish contribution to Geosites Project.

Today, the National Inventory initiated by the Spanish Geological Survey in the 70s only covers 40 % of the spanish territory (García-Cortés *et al*., 2001). However, the regional governments have made major contributions developinged regional inventories covering almost 90 % of the territory; this is the case of the Aragón Government.

The regional inventory of areas with geological values developed by the Aragon Government is presented in this study. These areas are not strictly protected by any law, but are areas of a great value from the landscape and geoscientific point of view. Six sites of geological interest area located (Map 12) within the study area. These are:

- *Galacho de Juslibol*: in the local terminology, *galachos* are meanders abandoned by the rivers, separated of these and in process of siltation. As a result, *Galacho de Juslibol* is a good example of the dynamic characteristics of meandering rivers (Figure 27).

- *Galacho de La Alfranca*: it is also a meander abandoned by the Ebro River in the course of its dynamic evolution. It is one of the best examples of abandoned meanders in the Iberian Peninsula (Figure 22.

- *Diapiro de Mediana*: located in the outcrops and generated in the exploitation of a gravel pit in a high terrace of the Ebro River in the south-eastern area. It is a deformation due to the diapiric activity related to a set of gypsums and marls (Figure 42 and 43).

- *Escarpe del Ebro en Villafranca de Ebro*: scarp of the Ebro in *Villafranca de Ebro* municipality. This scarp, produced by the Ebro River in its evolution, shows frequent examples of the slope dynamics in scarps on evaporitic deposits. Several rotational slides can be observed here (Figure 44).

- *Tollo del barranco de Villafranca de Ebro*: the *Villafranca de Ebro* Valley is an old flat bottom valley with a muddy filling, affected by gully erosion, locally denominated *tollos*. These are approximately 8 m deep and between 2 and 8 m wide.

- *Valles colgados del escarpe de Alfajarín*: here the gypsum scarp of *Alfajarín* presents several examples of hanging-valley (Figure 45 and 46).

Figure 42: *Diapiro de Mediana* located in a gravel pit near *Mediana*. Photo by José Luis Simón.

Figure 43: Detail of the top part of the *Diapiro de Meidana.* Photo by José Luis Simón*.*

Figure 44: Scarp of the Ebro river in *Villafranca de Ebro* municipality. Photo by José Luis Peña-Monne. July 1992.

Figure 45: Hanging-valleys in the gypsum scarp in the proximity of A*lfajarín* village. Photo by José Luis Peña-Monne.

Figure 46: Detail of one hanging-valley in the gypsum scarp in Alfajarín. Photo by José Luis Peña-Monné. Januar 1994.

4.2.7. Wetlands

According to the Ramsar Convention on Wetlands (**http://www.ramsar.org**), these are defined as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres".

The Convention on Wetlands, signed in Ramsar, Iran, in 1971, is an intergovernmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.

In the Aragon Region two areas are included in the Ramsar List of Wetlands of International Importance (*Laguna de Gallocanta y Laguna de Chiprana*). Recently, the Aragon Government has also created a regional inventory of wetlands. The main objective of this inventory is the maintenance and conservation of these areas in the Aragon Region, as a consequence of the observed decrease by 60%, due to anthropic factors. This initiative is really remarkable. Information related to the characteristics and location of these wetlands can be downloaded from the Aragon Government web page. However, only the main oxbows in the study area (*Galacho de Juslibol, La Alfancra, Cartuja* and *El Burgo*) and a small pond (*Balsa de Larralde*) are included in this inventory (Map 13).

Since it was believed that these areas should be also protected due to their environmental values, as they are also refuge of many bird species, Map 13 shows a wider cartography of wetlands in the study area. The information from the area upstream of Zaragoza was obtained from Néstor Jiménez Torrecilla, from the Faculty of Geology. The area downstream Zaragoza was personally digitised with the *SIG Oleícola* air photograph dated 1997 from the Ministry of Agriculture (M.A.P.A., 1997b). The digitized areas correspond to the more vegetated areas proximal to the river (natural vegetated areas and poplar plantations) as well as small depression filled in some cases with water.

Many of these spaces are already protected and included in the areas of the Natural Resources Management Planning of the thickets and oxbows of the Ebro River (PORN), Special Conservation Areas (SACs) and Special Protection Areas (SPAs). But there are still some areas with no form of protection, especially in the Ebro River upstream of Zaragoza and *Huerva, Jalón* and *Gállego* Rivers. Some of these areas correspond to salty wetlands whose origin, according to Sánchez-Navarro *et al.* (2004), is caused by the drainage of the Tertiary Aquifer into the Quaternary Aquifer, which caused the subsidence of the terrain. The extension of these salty lakes has extremely diminished in the last decades, especially in the surroundings of *Casetas* (Figure 47). In agreement with Sánchez-Navarro *et al.* (2004), the remaining areas (*Ojos del Cura, Ojo del Fraile, Torre del Chocolatero* and *Ojos de Matamala*) should be protected in view of their great fauna and flora biodiversity.

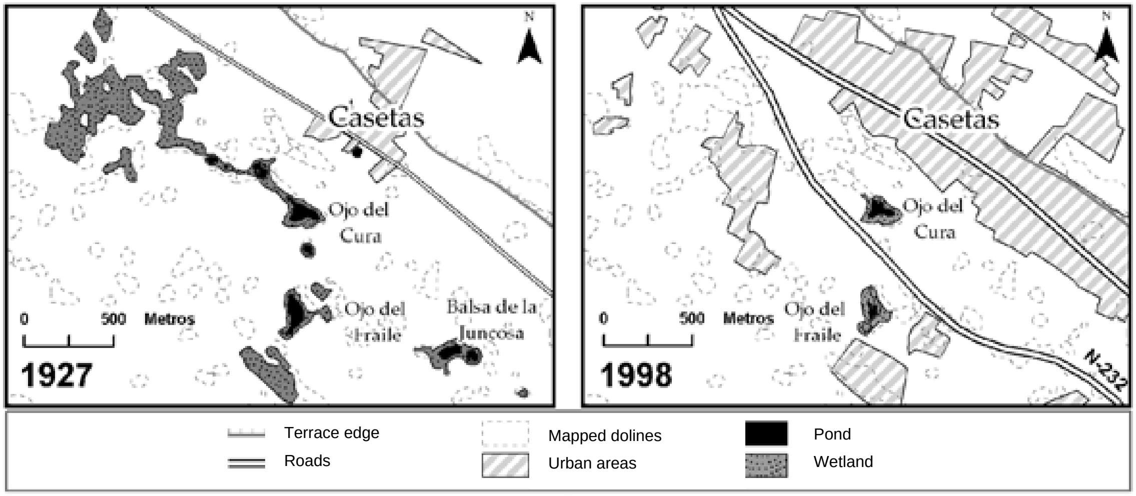


Figure 47: Extension of the wetlands in the surroundings of Casetas in 1927 and 1998. Source: Sánchez-Navarro *et al.* (2004).

4.2.8. Other areas

This chapter describes two areas of *Pinus halepensis* forest: natural and reforested area in the case of the forest located in the slope of *La Muela* structural platform, and only reforested in the case of the *Montes de Torrero* area, immediately south of Zaragoza city. In the case of the area near *La Muela*, this space corresponds to one of the scarce areas where the vegetation level of *Pinus halepensis* and *Quercus coccifera* are represented. This vegetation level is also found on the *La Plana* slopes and is included in the SACs and ASPs catalogue. Besides, the area is one of the rare forests outside the surroundings of the river shores.

In the case of *Montes de Torrero*, although it is a reforested area, it is included in the urban nucleus of Zaragoza and, due to demands of green areas and shadow by the population, this space is now under protection by the Zaragoza Council, and has a special land-use and landscape planning (Map 13).

In addition to these spaces, those protected by the Zaragoza Council with regard to urban and industrial uses may be also included here. Map 14 shows these areas according to the classification of the terrain from the land management planning of Zaragoza city. These areas of no urban development (SNU) are:

- SNU EN (CC): Natural ecosystems (EN); river bed, canals.
- SNU EN (MA): Natural ecosystems; forest cover.
- SNU EN (NI): Natural ecosystems; others.
- SNU EN (RF): Natural ecosystems; reforestation.
- SNU EN (SE): Natural ecosystems; steppe.
- SNU EN (SR): Natural ecosystems; thickets, oxbows, river banks.
- SNU EN (VB): Natural ecosystems; gullies.
- SNU EP (HH): Special protection (EP); orchard.
- SNU EP (R): Special protection (EP); traditionally irrigated land.
- SNU EP (S): Special protection (EP); traditionally dry land.

- SNU EP (V): Special protection (EP); flat bottom valleys.
- SNU ES (SCI): Special protection (EP); services land
- SNU ET: Ebro transition

4.3. Agricultural capability of the soil

The general agricultural capability of the soil was defined using the Cervatana model (C.S.I.C., 1996; de la Rosa *et al.*, 2002, 2004), which forecasts the general land-use capability or suitability for a broad series of possible agricultural uses (see charpter 2.3.3.4.). This model, which belongs to the MicroLEIS system (Mediterranean Land Evaluation Information System), was developed by de la Rosa and Magaldi (1982), with Mediterranean Region information, although other major components allow universal application.

Since the 1990s this system has evolved towards an agro-ecological decision support system. The original project corresponds to a set of qualitative land evaluation methods converted to PC computer programs to automate their application. Today, MicroLEIS DSS is a set of useful tools for decision-making within a wide range of agro-ecological schemes and is available in the following web page: **http://www.microleis.com** (de la Rosa *et al.*, 2004).

As mentioned in chapter 2.3.3.4., this model was also applied successfully in the surroundings of the study area at a lower scale (Machín and Navas, 1994, 1995; Navas and Machín, 1994, 1997), thus rendering it useful for such areas.

The prediction of general land-use capability is the result of a qualitative evaluation process or overall interpretation of the following biophysical factors: relief, soil, climate, and current land use or vegetation (Figure 48).

The most important aspects of such an evaluation system can be summed up as follows (C.S.I.C., 1996):

- The spatial unit of the study or reference is the land-unit, which includes both the characteristics of the soil and other ecological aspects: macro-topography, climate, current land use and vegetation.

- Prediction of potential land-use capability is not contemplated after major improvements or development such as irrigation or desalinisation.

- Socio-economic factors affecting any productive process are not considered, as this is exclusively a system of biophysical evaluation.

- The land-units are grouped in four classes. The first three - S1, S2 and S3 - include land considered capable of supporting continuing, intensive agricultural use, while land of class N is more appropriate for farming or forestry.

- Appropriate subclasses are established depending on the limiting factors or diagnostic criteria selected - site, soil, erosion risk and bioclimatic deficiency. In each case, the most-limiting criteria are given priority, up to a total of three.

- The procedure of maximum limitation is used, with matrices of degree, to relate the land characteristics directly with the classes of use capability.

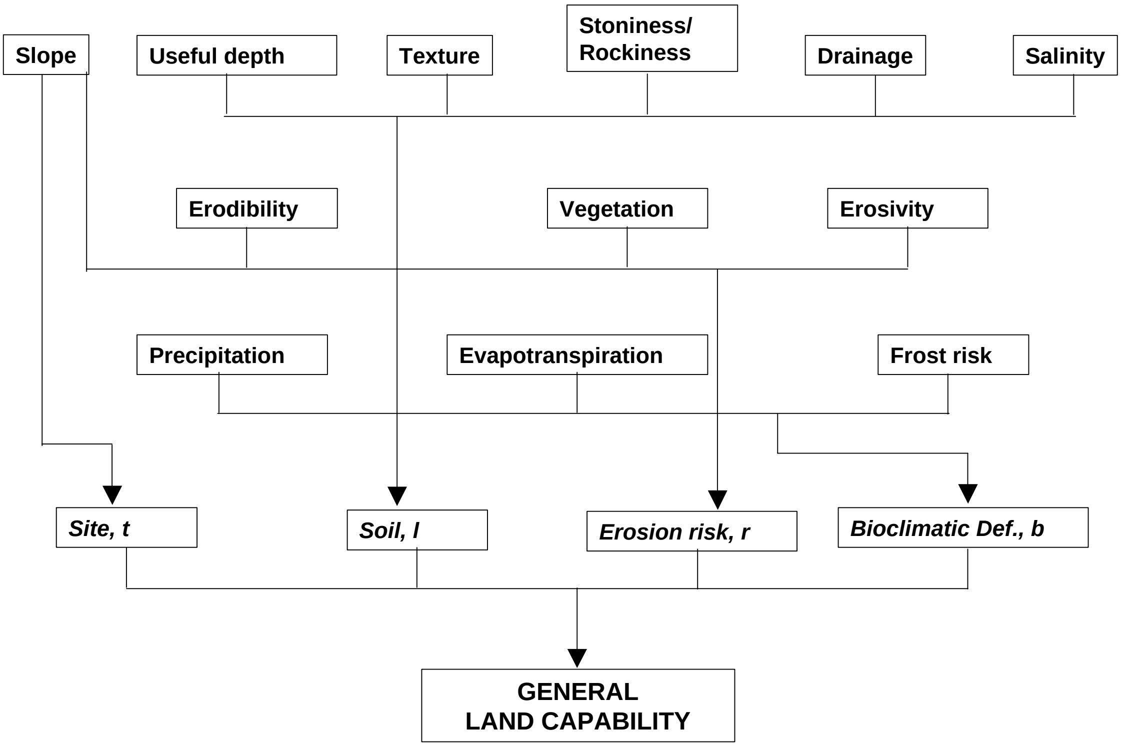


Figure 48: Factors used in general land capability (source: C.S.I.C., National Centre of Scientific Investigations, 1996). Letters *t, l, r* and *b* represent the site, soil, erosion and bioclimatic factors respectively when assigning the class capability (see tables 7, 8, 10, 11, 12, 13, 14, 15).

As mentioned before, prediction of potential land-use capability is not contemplated after major improvements or development such as irrigation or desalinisation. Thus, the general capability of the soil will be used for the land-use suitability analysis, in the cases of industrial and urban locations. However, in the case of irrigation, a special approach is used, based on the Cervatana model (C.S.I.C., 1996; de la Rosa et al., 2002, 2004), considering specific characteristics of soils prone to irrigation. Besides, this approach is also used for extraction locations, as these two uses compete directly in the same areas, the alluvial terraces and pediments.

In the next chapter, the division in homogeneous units and the classification of these units with respect to the different factors considered in Cervatana model (C.S.I.C., 1996; de la Rosa *et al.*, 2002, 2004) is developed. Afterwards, the general capability of the soil is presented, to finally proceed with the specific characterization of soils to potential irrigation.

4.3.1. Homogeneous unit mapping

The first step for the model development was the division of the study area in homogeneous units. As explained above, many criteria are used by different branches of the Landscape Science for division into homogeneous units: geomorphology, vegetation, soil, etc. In our opinion physiography best approximates the results of a landscape classification following a holistic approach. This why geomorphology was used as the main criteria for the division in homogeneous units (see chapter 2.3.3.4.).

However, land cover also plays an important role in landscape appearance. Thus, it was selected as the second criteria for a more detailed division in homogeneous units. Consequently, two cartographies were reclassified and combined, resulting in an homogeneous unit map.

First, the geological maps scale 1:50,000, from ITGE, were reclassified into seven geomorphological units (Table 5). The structural platforms were included in the degraded reliefs in Tertiary materials, due to their low extension. Glacis and alluvial fans were joined as a result of their coluvial origin and lithological similarity. Nevertheless, the small endorheic areas were kept as a unique category, as a result of their exceptional character with respect to the soil in the study area (Map 15).

A second reclassification was made to the CORINE (Coordination of information on the Environment) Land Cover map, scale 1:100,000 (Table 6). The resulting five categories were grouped, as in the case of the Geological map, taking into account the final objective: the agricultural capability model, but also the erosion susceptibility model, whose methodology is also based in the division in homogeneous units. Consequently, all human infrastructures were grouped into a unique category. The forest category was added to irrigated land due to its scarce extension, which is almost always linked to rivers and irrigated area proximity (Map 16). The reclassification and union of both maps results in fourteen homogeneous units (Map 17). These are:

- 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 bottom valleys with non-irrigated arable land.
- Flat bottom valleys with sclerophyllous vegetation.
- Glacis and alluvial fans with non-irrigated arable land.
- Glacis and alluvial fans with permanently irrigated land.
- Degraded slopes in Tertiary materials with sclerophyllous vegetation.
- Degraded slopes in Tertiary materials with non-irrigated arable land.
- Endorheic areas with permanently irrigated land.
- Water bodies.
- Human infrastructures.

Table 5: Reclassification of geomorphology. Source: Geological map, scale 1:50,000, ITGE.

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 sandstones	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	Late Pleistocene	Terrace (T4B- Huerva)	High terraces
Gravels, sands, silts and clays	Quaternary	Late Pleistocene	Terrace 30 m (T4)	High terraces
Gravels, sands, silts and clays	Quaternary	Late 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 6: Reclassification of CORINE (Coordination of information on the Environment) Land Cover map (2004). Code UE is the identification given to the different land covers in the CORINE (Coordination of information on the Environment) land-use project.

Code UE	Land cover description	Land cover homogeneous units
11100	Continuous urban fabric	Human infrastructures
11210	Discontinuous urban fabric	Human infrastructures
11220	Discontinuous urban fabric	Human infrastructures
12110	Industrial or commercial units	Human infrastructures
12120	Industrial or commercial units	Human infrastructures
12210	Road and rail networks and associated land	Human infrastructures
12220	Road and rail networks and associated land	Human infrastructures
12400	Airports	Human infrastructures
13100	Mineral extraction sites	Human infrastructures
13200	Dump sites	Human infrastructures
13300	Construction sites	Human infrastructures
14100	Green urban areas	Human infrastructures
14210	Sport and leisure facilities	Human infrastructures
14220	Sport and leisure facilities	Human infrastructures
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

4.3.2. Factor site

Table 7 shows the matrix of degree to relate land characteristics to land-use classification for the factor site, which is determined by the slope.

Table 7: Matrix of degree for factor site.

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

The classes were assigned to every homogeneous unit using the tool zonal statistics in ArcGIS applied to both homogeneous units and the information from the Digital Elevation Model from the Ministry of Agriculture, pixel size 20x20 m (M.A.P.A., 1997a). It returns the mean slope of every homogeneous unit, and this value is used to classify this unit into the land-use classes (S1, S2, S3 and N). Table 8 shows the mean slope value and the capability class assigned to every homogeneous unit. In general, the slope does not seem to be a limiting factor for the agricultural capability of the soil in our study area. Only the degraded slopes in Tertiary materials, occupied by sclerophyllous vegetation, present high values of slope percentage and, as a consequence, moderate agricultural capability with respect to the factor slope.

Table 8: Capability classes assigned to the homogeneous units.

Landsacape homogeneous units	**Slope %**	**Capability class**
Flood plain with non-irrigated arable land and sclerophyllous vegetation	3.7	S1t
Flood plain with permanently irrigated land and forest	0.6	S1t
High terraces with non-irrigated arable land	3.0	S1t
High terraces with permanently irrigated land	1.2	S1t
High terraces with sclerophyllous vegetation	9.6	S2t
Flat bottom valleys with non-irrigated arable land	8.1	S2t
Flat bottom valleys with sclerophyllous vegetation	11.2	S2t
Glacis and alluvial fans with non-irrigated arable land	2.8	S1t
Glacis and alluvial fans with permanently irrigated land	2.2	S1t
Degraded slopes in Tertiary materials with sclerophyllous vegetation	18.8	S3t
Degraded slopes in Tertiary materials with non-irrigated arable land	10.4	S2t
Endorheic areas with permanently irrigated land	0.7	S1t
Water bodies	No-data	No-data
Human infrastructures	No-data	No-data

4.3.3. Factor soil

As Figure 48 shows more information about the characteristics of the soils in the study area is required for the model development. The lack of a detailed soil map at scale 1:50,000 in the area determined the creation of a morpho-edaphic unit map (see chapter 3.1.6.). Moreover, some properties of the soil are indispensable factors in the determination of the erosion susceptibility and in the protection of groundwater bodies. Thus, a morpho-edaphic unit map was developed, starting from the division in homogeneous units.

Soil formation depends on several landscape factors: climate, parent material, vegetal cover, slope, etc. (Alberto *et al*. 1984; Badía, 1999; Rodríguez-Ochoa and Artieda, 1999). Therefore, in a geosystemic concept, different specified landscape units enable the creation of a morpho-edaphic or geo-edaphic unit map (Saz-Gonzalvo, 2001).

The assignment of soils to different homogeneous units (Table 9, Map 18) is based on a revision of previous works carried out in our study area. Alberto *et al*. (1984) studied the Quaternary of the Ebro Basin in the Aragon Region adding a cartography of soils, scale 1:200,000. In addition, a soil map, scale 1:250,000, was performed by the C.S.I.C. (*Consejo Superior de Investigaciones Científicas*), and some soil maps were included in the National forest map, scale 1:200,000, from the Institute for Nature Conservation (I.C.O.N.A.).

Many authors have stated that the existence of different geomorphological units permits a differentiation into several soil groups (Albareda *et al*., 1961; Alberto *et al*., 1984; Desir, 2001). Therefore the geomorphological component of the landscape units determines the type of soil assigned to every homogeneous unit.

Table 9: Soil assignation to the homogeneous units.

Landsacape homogeneous units	Morpho-edaphic units
Flood plain with non-irrigated arable land and sclerophyllous vegetation	Calcaric Fluvisols
Flood plain with permanently irrigated land and forest	Calcaric Fluvisols
High terraces with non-irrigated arable land	Petric Calcisols
High terraces with permanently irrigated land	Petric Calcisols
High terraces with sclerophyllous vegetation	Petric Calcisols
Flat bottom valleys with non-irrigated arable land	Haplic Gypsisols
Flat bottom valleys with sclerophyllous vegetation	Haplic Gypsisols
Glacis and alluvial fans with non-irrigated arable land	Calcaric Cambisols
Glacis and alluvial fans with permanently irrigated land	Calcaric Cambisols
Degraded slopes in Tertiary materials with sclerophyllous vegetation	Calcaric Regosols
Degraded slopes in Tertiary materials with non-irrigated arable land	Calcaric Regosols
Endorheic areas with permanently irrigated land	Haplic Solonchaks
Water bodies	Water bodies
Human infrastructures	Human infrastructures

In order to determine the characteristics of different soil types required for the model (texture, rockiness, useful depth, drainage, salinity), some detailed studies of soils and their agricultural capability, carried out in the proximity of the area, were revised, and the values of the soil properties were used (Machín and Navas, 1994, 1995, 1998).

Table 10 shows the matrix of degree for the factor soil, according to the Cervatana model (C.S.I.C., 1996; de la Rosa *et al.*, 2002, 2004). These levels are established in accordance to the intrinsic characteristics of the soils, determined by the F.A.O. (1976).

Table 10: Matrix of degree for the soil factor. (dS/m is deciSiemens per meter, salinity measure)

Capability class	Description	Useful depth (cm)	Texture	Rockiness %	Drainage	Salinity (dS/m)
S1l	Excellent	> 75	Well-balanced or hard	< 15	Good	< 1
S2l	Good	50-75	Light	15-40	Moderate	4-8
S3l	Moderate	25-50	-	>40	Deficient	8-12
Nl	Marginal	< 25	-	-	-	> 12

Table 11 presents the values assigned to every homogeneous unit according to the data of the properties of the different soils, gathered from the previous studies. The most limiting factor in the study area is salinity and, as a consequence, bad drainage existing in Haplic Solonchaks. Calcaric Regosols located in the degraded slopes also present moderate agricultural capability, due to the low useful depth of the profile. The rest of soils show excellent or good capability for agriculture.

Table 11: Capability classes assigned to the landscape units in relation to soil properties.

Landsacape homogeneous units	Morpho-edaphic units	Useful depth (cm)	Texture	Rockiness %	Drainage	Salinity (dS/m)
Flood plain with non-irrigated arable land and sclerophyllous vegetation	Calcaric Fluvisols	S1l	S1l	S1l	S1l	S1l
Flood plain with permanently irrigated land and forest						
High terraces with non-irrigated arable land	Petric Calcisols	S2l	S1l	S2l	S1l	S1l
High terraces with permanently irrigated land						
High terraces with sclerophyllous vegetation						
Flat bottom valleys with non-irrigated arable land	Haplic Gypsisols	S1l	S1l	S1l	S2l	S1l
Flat bottom valleys with sclerophyllous vegetation						
Glacis and alluvial fans with non-irrigated arable land	Calcaric Cambisols	S1l	S1l	S2l	S1l	S1l
Glacis and alluvial fans with permanently irrigated land						
Degraded slopes in Tertiary materials with sclerophyllous vegetation	Calcaric Regosols	S3l	S1l	S1l	S11l	S1l
Degraded slopes in Tertiary materials with non irrigated arable land						
Endorheic areas with permanently irrigated land	Haplic Solonchaks	S1l	S2l	S1l	S3l	Nl

4.3.4. Factor erosion risk

Four variables determine the erosion risk as limiting factors for good agricultural capability. Table 12 shows the matrix of degree of capability for these four factors (erodibility of the soils, slope, vegetation density, rain erosivity). The values, in this case, have been adapted from the CORINE (Coordination of information on the Environment) project.

The soil erodibility is considered low in soils of more than 75 cm of useful depth, silty texture and more than 10% rockiness. Moderate erodibility is present in soils of between 25 and 75 cm useful depth, well-balanced or sandy texture and less than 10% rockiness. Finally, high erodibility is present in soils with less than 25 cm of useful depth, silty texture and less than 10% stoniness.

The rain erosivity is measured with the factor *R*. This factor is the result of dividing *Fi* by *Hi*, being *Fi* the maximum annual precipitation, and *Hi* annual precipitation divided by evapotranspiration.

Table12: Matrix of degree for factor erosion risk.

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 13 shows the values of capability assigned to every homogeneous unit. The same value of rain erosivity has been given to all the units. Data from Ministry of Agriculture for the agro-climatic characterization of Zaragoza Province (M.A.P.A., 1987) were used. Vegetation density has been assigned according to the erosion risk model developed by van Zuidam (1976), in which different percentages of vegetation density are assigned to different land cover types.

Table 13: Capability classes for the factors of erosion risk.

Landsacape homogeneous units	Soils erodibility	Slope %	Vegetation density %	Rain erosivity
Flood plain with non-irrigated arable land and sclerophyllous vegetation	S1r	S1r	S2r	S1r
Flood plain with permanently irrigated land and forest	S1r	S1r	S1r	S1r
High terraces with non-irrigated arable land	S2r	S1r	S2r	S1r
High terraces with permanently irrigated land	S2r	S1r	S1r	S1r
High terraces with sclerophyllous vegetation	S2r	S1r	S2r	S1r
Flat bottom valleys with non-irrigated arable land	S1r	S1r	S2r	S1r
Flat bottom valleys with sclerophyllous vegetation	S1r	S1r	S2r	S1r
Glacis and alluvial fans with non-irrigated arable land	S2r	S1r	S2r	S1r
Glacis and alluvial fans with permanently irrigated land	S2r	S1r	S1r	S1r
Degraded slopes in Tertiary materials with sclerophyllous vegetation	S2r	S2r	S2r	S1r
Degraded slopes in Tertiary materials with non-irrigated arable land	S2r	S1r	S2r	S1r
Endorheic areas with permanently irrigated land	S1r	S1r	S1r	S1r

4.3.5. Bioclimatic deficiency

The degree matrix for bioclimatic deficiency was developed according to Terraza model, also created for the MicroLEIS system (Table 14). The aridity is expressed as a ratio between annual precipitation and annual evapotranspiration. According to the agro-climatic characterization of Zaragoza Province, annual precipitation is about 350 mm in the study area and evapotranspitation about 850 mm. This results in an aridity index of 0.41. Thus, all the study area attains moderate agricultural capability with respect to aridity factor (Table 15).

The frost risk is assigned according to the number of months in the year with mean minimum temperatures less than 6 ºC. According to the agro-climatic characterization, Zaragoza experiences between 4 and 6 months with a mean minimum temperature under 6 ºC. In addition, according to Hernández-Navarro (1995) the number of days in Zaragoza with temperatures below 7 ºC, which is the threshold for vegetation rest, is 69 (more than 2 months). Therefore, all the homogeneous units have good agricultural capability with respect to frost risk (Table 15).

Table 14: Matrix of degree for bioclimatic deficiency factor.

Capability class	Description	Aridity	Frost risk
S1b	Excellent	Low > 0,75	Null 0< 2
S2b	Good	Moderate 0,75-0,5	Moderate 2-5
S3b	Moderate	High 0,50-0,33	High > 5
Nb	Marginal	Very high < 0,33	-

Table 15: Agricultural capabilities classes for bioclimatic deficiency factor.

Landsacape homogeneous units	Aridity	frost risk
Flood plain with non-irrigated arable land and sclerophyllous vegetation	S3b	S2b
Flood plain with permanently irrigated land and forest	S3b	S2b
High terraces with non-irrigated arable land	S3b	S2b
High terraces with permanently irrigated land	S3b	S2b
High terraces with sclerophyllous vegetation	S3b	S2b
Flat bottom valleys with non-irrigated arable land	S3b	S2b
Flat bottom valleys with sclerophyllous vegetation	S3b	S2b
Glacis and alluvial fans with non-irrigated arable land	S3b	S2b
Glacis and alluvial fans with permanently irrigated land	S3b	S2b
Degraded slopes in Tertiary materials with sclerophyllous vegetation	S3b	S2b
Degraded slopes in Tertiary materials with non-irrigated arable land	S3b	S2b
Endorheic areas with permanently irrigated land	S3b	S2b

4.3.6. General agricultural capability mapping

As cited above, the procedure of maximum limitation is used for assigning agricultural capabilities. Thus, every homogeneous unit attains the agricultural capability of the most limiting factor (Map 19).

Most of the study area is included in category S3, land with moderate use capability and with climate as the limiting factor. These areas substantially reduce the range of possible crops and the productive capability. Management techniques are more difficult to apply and maintain, with higher costs. Intensive practices are necessary 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 soil and climate are limiting factors. Slope is an additional limiting factor in the degraded areas covered by sclerophyllous vegetation. Finally, the endorheic areas are included in the N class (marginal or non-productive land).

4.3.7. Irrigation capability of the soil mapping

The methodology used is an adaptation of the values and parameters of the soils, specific for irrigation, to the system of maximum limitation of the Cervatana model (C.S.I.C., 1996; de la Rosa *et al.*, 2002, 2004). In a final step in the project, the results will be used in the suitability analysis for new irrigated areas (see chapter 6.1.2.2.). In this analysis, other factors such as slope and erosion hazard will be considered. Thus, this approach is only applied to the factor soil, in order to avoid redundancy.

Table 16 shows the matrix of degree for the factor soil. The parameters used and their classes are assigned and based on those used by Ana Navas and Javier Machín for a study performed in the Ebro Basin, in which the construction viability of an irrigation canal, located on the right bank of the river, is analysed (INARSA, 1992). Many criteria, used by these authors to classify the soils in relation to their irrigation capability, match the ones used in Cervatana model (C.S.I.C., 1996; de la Rosa *et al.*, 2002, 2004), *i.e*. drainage, rockiness, useful depth and texture.

Table 16: Capability classes and factor ranges used for the irrigation capability of soils. SAR is the sodium absorption ratio, which expresses the sodium in comparison with the calcium plus magnesium.

Capability description	Useful depth (cm)	Texture	Rockiness %	Drainage	Electrical conductivity (dS/m)	Carbonate %	Gypsum %	SAR
Excellent	> 75	Well-balanced or light	< 15	Good	< 8	< 25	< 15	> 10
Good	60-75	Well-balanced or hard	15-50	Moderate	8-16	25-40	15-35	10-15
Moderate	40-60	Hard	>50	Deficient	> 12	> 40	35-75	> 15
Marginal	< 40	-	-	-	-	-	> 75	-

Table 17 shows the different morpho-edaphic units with the corresponding factor classes and, in the last column, the irrigation class, according to their limiting factor. The highest irrigation capability appears in the floodplain with Calcaric Fluvisols, which have a good capability, with only the carbonate content as limiting factor (Map 20). Petric Calcisols and Calcaric Cambisols also have good irrigation capability, but with a limiting factor of stoniness and carbonate. Calcisols have drainage as third limiting factor, while Cambisols present gypsum content as this factor. Gypsisols and Regosols only show moderate capability with gypsum as main limiting factor. And finally, solonchaks present marginal irrigation capability.

Table 17: Morpho-edaphic units and corresponding factors and irrigation classes.

Morpho-edaphic units	Useful depth (cm)	Texture	Rockiness %	Drainage	Electric conductivity (dS/m)	Gypsum %	Carbonate %	SAR	Irrrigation class
Calcaric Fluvisols	S1d	S1t	S1r	S1n	S1e	S1g	S2c	S1k	S2c
Petric Calcisols	S2d	S1t	S2r	S1n	S1e	S1g	S2c	S1k	S2drc
Haplic Gypsisols	S1d	S1t	S1r	S2n	S1e	S3g	S1c	S1k	S3g
Calcaric Cambisols	S1d	S1t	S2r	S1n	S1e	S2g	S2c	S1k	S2rcg
Calcaric Regosols	S3d	S1t	S1r	S1n	S1e	S3g	S2c	S1k	S3dg
Haplic Solonchaks	S1d	S2t	S1r	S3n	Ne	S1g	S1c	S1k	NI

5. Geo-hazards mapping

5.1. Erosion susceptibility

The methodology used for erosion susceptibility was developed by van Zuidam and van Zuidam-Cancelado (1979), who studied the geomorphology of the central Ebro Depression in detail (see chapter 2.3.3.5). They developed the “ITC, International Institute for Geo-Information Science and Earth Observation, system of terrain analysis, classification and evaluation”, which is based on a landscape approach.

In this system, the terrain is also divided in 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, soils), field work and expert knowledge. This is how the homogeneous units created for the agricultural capability of the soils map were used in the present project (see chapter 4.3.1.).

The parameters introduced in this model match the ones used in the majority of approaches revised (see chapter 2.3.3.5.). These are:

- Slope: slope steepness, slope length, slope form.
- Vegetation/Land use: vegetation density, land-use condition.
- Climatologic conditions: heavy rainstorm frequency.
- 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 surface.
- Conservation practices: in plain, in drainage ways.

Each terrain parameter or factor must then be classified and rated. A description of the classification and rating of the different homogeneous units, with respect to the different factors on erosion susceptibility, is presented in the next chapters (see chapters 5.1.1., 5.1.2., 5.1.3., 5.1.4., 5.1.5, 5.1.6.).

Finally all ratings are added together, and a classification of the landscape units is made according to their erosion susceptibility (see chapter 5.1.7).

5.1.1. Slope

The different terrain units are classified with respect to the slope, according to their slope steepness, length and shape. Tables 18, 19 and 20 show the ratings given to every class, according to slope steepness, slope length and slope shape, respectively (van Zuidam and van Zuidam-Cancelado, 1979).

Table 18: 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 19: 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 20: Slope shape classes. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Slope shape description	Rating
Concave	1
Convex	2
Straight	3

The slope steepness was evaluated following the procedure used for agricultural capability; the zonal statistic tool was applied to every homogeneous unit (see table 8 for slope percentage of every unit). Table 21 shows the rating assigned to every unit in relation to the three slope factors. Because of the diversity of lengths within every homogeneous unit and the impossibility to calculate these a slope length value of 4 (moderately long) was assigned to all the units. The description made by Alberto *et a*l. (1984) of the different geomorphological units of the Quaternary in the Ebro Depression and also expert knowledge was used for slope shape. Thus, almost all the units present straight slopes, as the flood plain and degraded slopes; the glacis and alluvial fans present convex slopes and the endorheic areas, concave slope.

Table 21: Rating of slope factors for the different homogeneous units.

Landsacape homogeneous units	Slope %	Slope length	Slope shape
Flood plain with non-irrigated arable land and sclerophyllous vegetation	2	4	3
Flood plain with permanently irrigated land and forest	1	4	3
High terraces with non-irrigated arable land	2	4	3
High terraces with permanently irrigated land	1	4	3
High terraces with sclerophyllous vegetation	4	4	3
Flat bottom valleys with non-irrigated arable land	4	4	3
Flat bottom valleys with sclerophyllous vegetation	4	4	3
Glacis and alluvial fans with non-irrigated arable land	2	4	2
Glacis and alluvial fans with permanently irrigated land	1	4	2
Degraded slopes in Tertiary materials with sclerophyllous vegetation	8	4	3
Degraded slopes in Tertiary materials with non-irrigated arable land	4	4	3
Endorheic areas with permanently irrigated land	1	4	1

5.1.2. Vegetation/land-use

The rating for this factor are assigned according to either vegetation density information or land-use condition information. In this case, the information of land cover from the CORINE (Coordination of information on the Environment) was used, since this factor was also used for the division in homogeneous units. Table 22 shows the ratings assigned to different vegetation density and land-use condition classes (van Zuidam and van Zuidam-Cancelado, 1979).

Table 22: 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 23: Rating for land-cover factor assigned to the terrain units.

Landsacape homogeneous units	Rating
Flood plain with non-irrigated arable land and sclerophyllous vegetation	4
Flood plain with permanently irrigated land and forest	1
High terraces with non-irrigated arable land	8
High terraces with permanently irrigated land	1
High terraces with sclerophyllous vegetation	4
Flat bottom valleys with non-irrigated arable land	8
Flat bottom valleys with sclerophyllous vegetation	4
Glacis and alluvial fans with non-irrigated arable land	8
Glacis and alluvial fans with permanently irrigated land	1
Degraded slopes in Tertiary materials with sclerophyllous vegetation	4
Degraded slopes in Tertiary materials with non-irrigated arable land	8
Endorheic areas with permanently irrigated land	1

Table 23 shows the ratings assigned to the homogeneous units, according to the description of CORINE (Coordination of information on the Environment) cartography. The adaptation of the values to the descriptions and ratings assigned by van Zuidam and van Zuidam-Cancelado (1979) was performed on the basis of studies developed in the surroundings of the study area (Desir, 2001; Ries, 2002). Thus, irrigated land and forest obtain the lowest ratings, according to their low susceptibility to erosion, and dry arable land achieve the highest values, even more than the sclerophyllous vegetation, possibly because of the existence of a lichen crust in the soils in the areas occupied by shrubs.

5.1.3. Climate

The factor climate was classified on the basis of heavy rainstorm frequency. Table 24 shows the classes developed for this factor. In this case, the whole study area obtains value 4, because heavy rainstorms occur more than once a year **(**van Zuidam and van Zuidam-Cancelado, 1979).

Table 24: Climate factor classes. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Heavy rainstorm frequency	**Rating**
Exceptional	1
Once a year	2
Several times a year	4

5.1.4. Erosion and mass movement

Four different variables are analysed for the erosion and mass movement factor. First, the rating of wind erosion, which, according to this method, can be classified on the basis of the presence or absenceof an A horizon in the soil profile and its textural characteristics. But, in addition to this characteristic, it was classified it 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 25 shows the rating for the different classes (van Zuidam and van Zuidam-Cancelado, 1979).

Table 25: Wind erosion classes and ratings. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Wind erosion	**Rating**
None	0
Slight	1
Moderate	2
Severe	4

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 26), and the absence of A horizon is evidence of severe sheet erosion (rating 4, according to Table 26) (van Zuidam and van Zuidam-Cancelado, 1979).

Table 26: Sheet erosion classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Sheet erosion	Rating
None	0
Slight	1
Moderate	2
Severe	4

Table 27 shows the ratings of the third factor, rating of rill, gully and ravine erosion. This factor is classified according to the depth and frequency of rills in the terrain (van Zuidam and van Zuidam-Cancelado, 1979).

Table 27: Rill and gully erosion classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Rill-gully erosion	Rating
None	0
Slight	1
Moderate	2
Severe	4

The last factor is mass movement hazard rating. Table 28 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 28: Mass movement classes and ratings. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Mass movement hazard	Rating
None	0
Slight	1
Moderate	2
Severe	4

Table 29 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.

Table 29: Rating assigned to every homogeneous unit, according to erosion factor.

Landsacape homogeneous units	Wind erosion	Sheet erosion	Rill-gully erosion	Mass movement
Flood plain with non-irrigated arable land and sclerophyllous vegetation	1	1	0	0
Flood plain with permanently irrigated land and forest	1	1	0	0
High terraces with non-irrigated arable land	2	2	0	0
High terraces with permanently irrigated land	1	1	0	0
High terraces with sclerophyllous vegetation	2	2	0	0
Flat bottom valleys with non-irrigated arable land	1	2	2	1
Flat bottom valleys with sclerophyllous vegetation	1	1	2	1
Glacis and alluvial fans with non-irrigated arable land	2	2	1	0
Glacis and alluvial fans with permanently irrigated land	1	1	1	0
Degraded slopes in Tertiary materials with sclerophyllous vegetation	2	4	4	2
Degraded slopes in Tertiary materials with non-irrigated arable land	2	4	4	2
Endorheic areas with permanently irrigated land	1	1	0	0

5.1.5. Soil and geology

With respect to the soil, the erosion is rated on the basis of useful depth, texture, sealing susceptibility and consolidation. Tables 30, 31, 32 and 33 show the ratings assigned to every class (van Zuidam and van Zuidam-Cancelado, 1979).

Table 30: 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 31: 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 32: 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 33: Consolidation classes and rating. Source: slightly modified after van Zuidam and van Zuidam-Cancelado (1979).

Consolidation	Rating
Firmly consolidated	1
Weekly consolidated	2
Non-consolodated	4

The assignment of ratings to the terrain units was carried out on the basis of the analysis and soils descriptions gathered from the previous studies developed in the area (Table 34).

Table 34: Soil factor rating assigned to every homogeneous unit.

Landsacape homogeneous units	Useful depth	Texture	Sealing susceptibility	Consolidation
Flood plain with non-irrigated arable land and sclerophyllous vegetation	1	1	3	4
Flood plain with permanently irrigated land and forest	1	1	3	4
High terraces with non-irrigated arable land	2	1	2	2
High terraces with permanently irrigated land	2	1	2	2
High terraces with sclerophyllous vegetation	2	1	2	2
Flat bottom valleys with non- irrigated arable land	1	8	3	4
Flat bottom valleys with sclerophyllous vegetation	1	8	3	4
Glacis and alluvial fans with non-irrigated arable land	1	1	3	4
Glacis and alluvial fans with permanently irrigated land	1	1	3	4
Degraded slopes in Tertiary materials with sclerophyllous vegetation	3	8	3	4
Degraded slopes in Tertiary materials with non-irrigated arable land	3	8	3	4
Endorheic areas with permanently irrigated land	1	4	3	4

In relation to geology, the structure of underlying strata and the depth of the below surface impermeable layers are assessed. In the case of the structure of underlying strata, all the study area achieves value 1, which corresponds to horizontally bedded strata (Table 35) (van Zuidam and van Zuidam-Cancelado, 1979).

Table 35: 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 36: 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

In the case of the depth of impermeable layer below surface (Table 36), the whole area receives value 0, since the gypsum formation forms the impermeable layers in the study area and the overlying Quaternary cover is usually deeper than 150 cm. The exception being the degraded reliefs, where the gypsum strata are only covered by Regosols, with useful depth of less than 50 cm (see Table 37 for ratings assigned to the homogeneous units).

Table 37: Rating assigned to every homogeneous unit, according to the strata structure and depth of impermeable layers.

Landsacape homogeneous units	Strata structure	Depth impermeable layers
Flood plain with non-irrigated arable land and sclerophyllous vegetation	1	0
Flood plain with permanently irrigated land and forest	1	0
High terraces with non-irrigated arable land	1	0
High terraces with permanently irrigated land	1	0
High terraces with sclerophyllous vegetation	1	0
Flat bottom valleys with non-irrigated arable land	1	0
Flat bottom valleys with sclerophyllous vegetation	1	0
Glacis and alluvial fans with non-irrigated arable land	1	0
Glacis and alluvial fans with permanently irrigated land	1	0
Degraded slopes in Tertiary materials with sclerophyllous vegetation	1	4
Degraded slopes in Tertiary materials with non-irrigated arable land	1	4
Endorheic areas with permanently irrigated land	1	0

5.1.6. Conservation practices

This factor refers to the agricultural practices used by man for erosion avoidance. There are two different factors: conservation practices in plain (Table 38), and conservation practices in drainage ways (Table 39). Both factors have negative values in relation to their ability to reduce erosion susceptibility (van Zuidam and van Zuidam-Cancelado, 1979).

Table 38: 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 39: 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

Table 40 shows the ratings assigned to the landscape units. 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.

Table 40: Rating assigned to every landscape unit, according to the conservation practices developed.

Landsacape homogeneous units	Conservation practices in plain	Conservation practices in drainage ways
Flood plain with non-irrigated arable land and sclerophyllous vegetation	0	0
Flood plain with permanently irrigated land and forest	-4	-2
High terraces with non-irrigated arable land	0	0
High terraces with permanently irrigated land	-4	-2
High terraces with sclerophyllous vegetation	0	0
Flat bottom valleys with non-irrigated arable land	-4	0
Flat bottom valleys with sclerophyllous vegetation	0	0
Glacis and alluvial fans with non-irrigated arable land	0	0
Glacis and alluvial fans with permanently irrigated land	-4	-2
Degraded slopes in Tertiary materials with sclerophyllous vegetation	0	0
Degraded slopes in Tertiary materials with non-irrigated arable land	0	0
Endorheic areas with permanently irrigated land	-4	-2

5.1.7. Erosion susceptibility mapping

As explained above (chapter 5.1.), a all ratings are added and landscape units are classified according to their erosion susceptibility (Table 41).

Table 41: Total score of rating for the different landscape homogeneous units and erosion susceptibility class.

Landscape homogeneous units	Slope	Veget. Land-cover	Clima	Eros.	Soil	Geolo.	Cons. Pract.	Total score	Erosion class
Flood plain with non-irrigated arable land and sclerophyllous vegetation	9	4	4	2	9	1	0	29	moderate
Flood plain with permanently irrigated land and forest	8	1	4	2	9	1	-6	19	weak
High terraces with non-irrigated arable land	9	8	4	4	7	1	0	33	moderate
High terraces with permanently irrigated land	8	1	4	2	7	1	-6	17	weak
High terraces with sclerophyllous vegetation	11	4	4	4	7	1	0	31	moderate
Flat bottom valleys with non-irrigated arable land	11	8	4	6	16	1	-4	42	high
Flat bottom valleys with sclerophyllous vegetation	11	4	4	5	16	1	0	41	high
Glacis and alluvial fans with non-irrigated arable land	8	8	4	5	9	1	0	35	moderate
Glacis and alluvial fans with permanently irrigated land	7	1	4	3	9	1	-6	19	weak
Degraded slopes in Tertiary materials with sclerophyllous vegetation	15	4	4	12	18	5	0	58	very-high
Degraded slopes in Tertiary materials with non-irrigated arable land	11	8	4	12	18	5	0	58	very-high
Endorheic areas with permanently irrigated land	6	1	4	2	12	1	-6	20	weak

Degraded slopes in Tertiary materials with irrigated land or sclerophyllous vegetation present the highest susceptibility values, mainly due to their high scores in the soil, slope and erosion factors. Flat bottom valleys covered by non-irrigated arable land or sclerophyllous vegetation also present a high degree of erosion susceptibility, caused by the bad characteristics of the soils and the slope. In this case, gully erosion is the the main erosion process (Map 21).

The lowest susceptibility to erosion values appears in flood plains, high terraces and pediments covered by irrigated land and forest. In this case, the lowest values in land cover factor determine the lowest values in erosion susceptibility, in addition to the conservation practices factor.

5.1.8. Change in erosion susceptibility when irrigating

In the case of erosion hazard, as for agricultural capability of the soil, a second approach was carried out in order to be introduced in the suitability analysis for the location of new irrigated areas. It consists of locating the areas that will reduce the erosion hazard when irrigated. The methodology described by van Zuidam and van Zuidam-Cancelado (1979) was applied under the assumption that the whole study area is irrigated land. Then, the erosion hazard model was applied. The only values that change are the land cover factor, which recieves value 1 for the whole study area, instead of the values given in Table 41, and the conservation practices, which also attains the same value (-6) for the whole study area.

Table 42 shows the new erosion factor values and the new assumed total erosion hazard score, compared to the previous total erosion hazard scores and the final change in erosion hazard. Map 22 shows the change in erosion regionalisation. Obviously, the areas already irrigated present null change in erosion hazard. The biggest change is found in the areas that are presently covered by non-irrigated arable land, located in high terraces, pediments and degraded slopes in Tertiary materials.

Table 42: Erosion hazard change values.

Landsacape homogeneous units	Slope	Veget. Land-cover	Clima	Eros.	Soil	Geolo.	Cons. Pract.	Assum. total score	Initial Total score	Erosion Hazard change
Flood plain with non-irrigated arable land and sclerophyllous vegetation	9	1	4	2	9	1	-6	20	29	9
Flood plain with permanently irrigated land and forest	8	1	4	2	9	1	-6	19	19	0
High terraces with non-irrigated arable land	9	1	4	4	7	1	-6	20	33	13
High terraces with permanently irrigated land	8	1	4	2	7	1	-6	17	17	0
High terraces with sclerophyllous vegetation	11	1	4	4	7	1	-6	22	31	9
Flat bottom valleys with non-irrigated arable land	11	1	4	6	16	1	-6	33	42	9
Flat bottom valleys with sclerophyllous vegetation	11	1	4	5	16	1	-6	32	41	9
Glacis and alluvial fans with non-irrigated arable land	8	1	4	5	9	1	-6	22	35	13
Glacis and alluvial fans with permanently irrigated land	7	1	4	3	9	1	-6	19	19	0
Degraded slopes in Tertiary materials with sclerophyllous vegetation	15	1	4	12	18	5	-6	49	58	9
Degraded slopes in Tertiary materials with non-irrigated arable land	11	1	4	12	18	5	-6	45	58	13
Endorheic areas with permanently irrigated land	6	1	4	2	12	1	-6	20	20	0

5.2. Doline susceptibility

The logistic regression technique has already been used for many environmental purposes, in many cases with more success than multiple linear regression. Battaglin and Goolsby (1997) compared the results of both techniques to identify natural and anthropogenic variables of drainage basins that have strong relations to agricultural chemical concentrations and mass transport measured in rivers. They concluded that logistic regression was somewhat more successful than multiple linear regression. This was one of the reason for its selection as methodology for doline susceptibility mapping in our project (Lamelas *et al.*, 2006a).

This technique has also been successfully applied to predict thresholds of channel pattern and instability (Bledsoe and Watson, 2001), and to forecast short term hail risk (Sánchez et al., 1998). But the most common use of this technique in geo-hazards has been the development of landslide hazard maps (Beguería and Lorente, 2003; Lee and Min, 2001; Ohlmacher and Davis, 2003).

Logistic regression establishes a functional relationship between the binary-coded hazard locations (existence or not of dolines) and different factors which are recognised to play a role in the hazard development. It states that the natural logarithm of odd (logit) is linearly related to the independent variables (Beguería and Lorente, 2003):

$$\text{Logit}(P) = \text{Ln}(P/\ 1\text{-}P) = B0+B1X1+\ldots+BnXn \qquad (1)$$

Where *P* is the probability of occurrence, *Xn* is the set of *n* independent variables, and *Bn* is the set of *n*+1 parameters. Developing expression 2:

$$P = \exp(B0+B1X1+\ldots+BnXn)/\ 1+\exp(B0+B1X1+\ldots+BnXn) \qquad (2)$$

Slope coefficients for the logistic equation are fit to the categorical data using a maximum likelihood method that optimises the probability that the observed data be estimated from the set of slope coefficients (Battaglin and Goolsby, 1997).

In ordinary regression analysis, the coefficient of determination (r^2) is frequently used as a measure of model performance. In logistic regression, it is common to be more concerned with whether the predictions are correct or incorrect than with how close the predicted values are to the observed values (0 or 1) of the dependent variables. Therefore, r^2 has little meaning in logistic regression analysis (Bledsoe and Watson, 2001).

Goodness-of-fit tests may aid in the interpretation of the results of logistic regression. The likelihood *L0* for the null model, where all slope parameters are zero, may be directly compared with the likelihood *L1* of the fitted model. Specifically, one can compute the x^2 statistic for this comparison as:

$$X^2 = -2\ (\log(L0) - \log(L1)) \qquad (3)$$

The degree of freedom for this X^2 value is equal to the number of independent variables in the logistic regression. If the p-level associated with this x^2 is significant, the estimated model yields a significantly better fit to the data than the null model and the regression parameters are statistically significant.

The application of these techniques implies a previous knowledge of the process, recognition of the controlling factor and its regionalisation. In addition, the application of this methodology starts from a good localization of existing dolines.

5.2.1. Process description and geological risk

Karst refers to a distinctive terrain that evolves through dissolution of the bedrock and development of efficient underground drainage (Waltham *et al.* 2005). It is therefore associated primarily with limestone, but also forms on other carbonates and other soluble rocks, *i.e.* evaporates, as it is the case in the study area.

An extensive playa-lake once covered the central sector of the Ebro Basin. Contiuing evaporation produced the Upper Oligocene–Lower Miocene Zaragoza Gypsum deposits (Quirantes, 1978; Riba et al., 1983; Ortı, 1990). It is a thick sequence comprising up to 3000 m of gypsum with anhydrite in depth and includes halite units up to 120 m thick (Torrescusa and Klimowitz, 1990). The Zaragoza Gypsum crops out in a wide area around Zaragoza (Gutiérrez-Elorza and Gutiérrez-Santolalla, 1998).

The solubilities of gypsum and halite in water, at 25°C and 1 atmosphere pressure, are respectively 2.4 g/l and 360 g/l (Ford and Williams, 1989). These high solubilities explain the greater intensity and rate of landscape development in salt and gypsum karst compared with that of limestone karst (Gutiérrez-Elorza and Gutiérrez-Santolalla, 1998).

An evolutionary approach to the typology of Karst has been elaborated by Klimchouk and Ford (2000). In this classification, types of Karst are viewed as successive stages of hydrogeological evolution (Figure 49).

Due to the high solubility of gypsum, surface exposures of evaporite karst are restricted to arid regions. Of the various types of Karst, exposed, soil-covered, and intrastratal karst are most common in evaporite rocks (White, 1988). two karstification types occur in the study area, uncovered karst and karst covered with mainly alluvial deposits.

In areas where bare gypsiferous formations crop out, without any type of cover, the karst landforms are mainly limited to karren, dispersed dolines and enclosed depressions (Gutiérrez-Elorza and Peña, 1994).

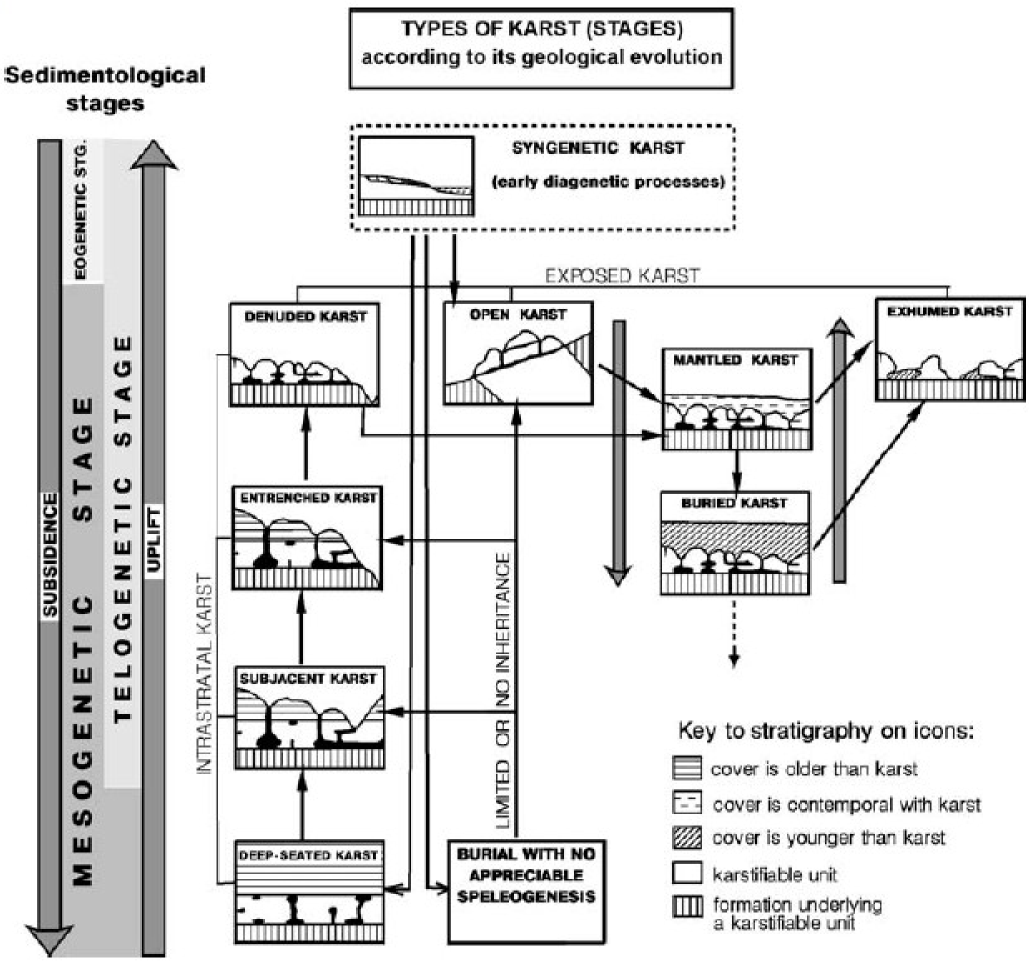


Figure 49: Evolutionary types of Karst. Source: Klimchouk and Ford (2000).

The karstification processes are particularly pronounced where the gypsum is covered by alluvial deposits (covered karst). Alluvial dolines are generated when superficial deposits (terraces and glacis) overlying Neogene evaporites fall into conduits enlarged by dissolution, causing depressions at the surface. Their generation follows two mechanisms (Soriano and Simón, 1995):

- Mobilisation of material by ground water, which may take place by either dissolution of soluble substrate or piping of the detrital cover (Figure 50).
- Cave-in of the alluvial cover, developed by either sudden collapse or slow subsidence (Figure 50).

According to Soriano and Simón (2002), present-day alluvial dolines, in a sector upstream of Zaragoza, show the shapes described in classical papers (Cvijic, 1981; Palmquist, 1979): pan, funnel and well-shaped types have been identified. The doline size is variable, their diameters range between several meters to 100 m, and their depths between 1 and 20 m. There are also larger shallow depressions up to 1,100 m long and 600 m wide, most of them identifiable as karst velleys (uvalas). They observed that, in this sector, dolines are preferentially located in the second terrace levels. There is a notable decrease in doline density in the flood plain. Besides, the subsidence in different dolines during a period of about 4 years was monitored, indicating subsidence rates ranging from 21 to 92 mm/year (Soriano and Simón, 2002).

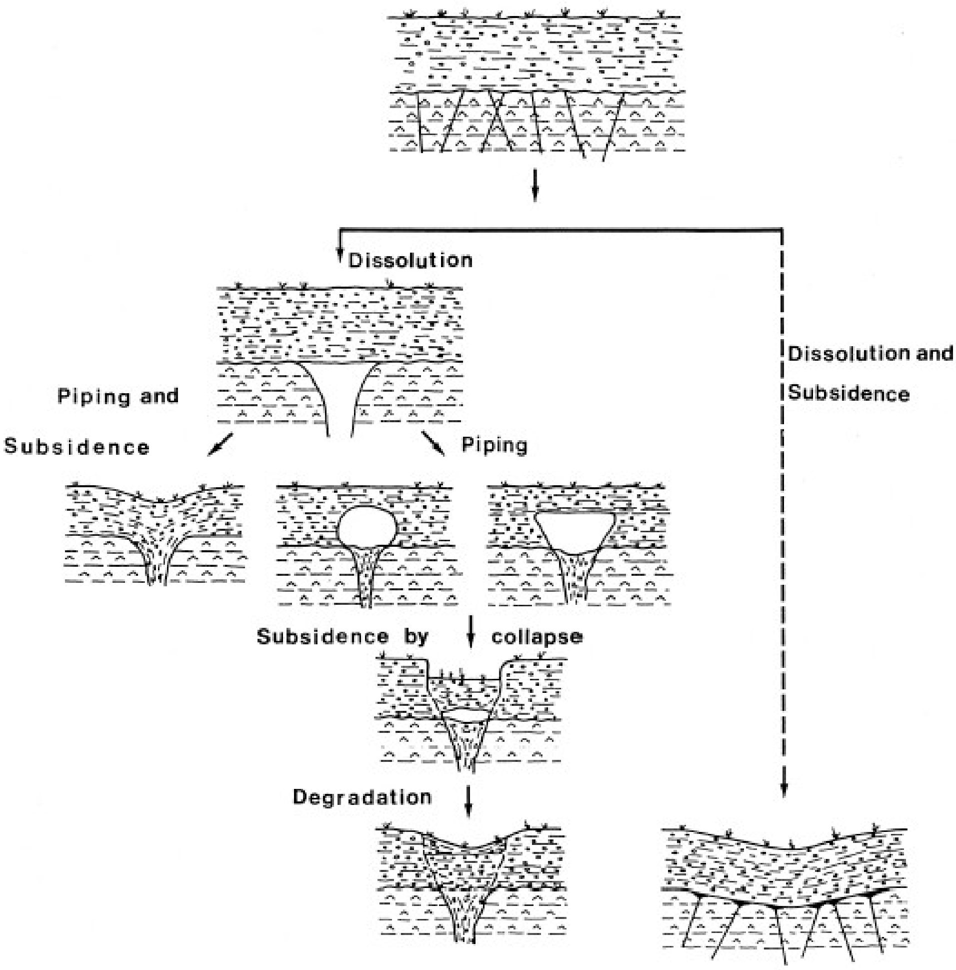


Figure 50: Processes involves in alluvial dolines development. Source: Gutiérrez-Elorza and Gutiérrez-Santolalla (1998).

In the sector downstream of Zaragoza, most of the dolines are shallow closed depressions, commonly less than 1.5 m deep, with non-scarped edges. They display highly variable geometries and dimensions, reaching up to 0.35 km^2 in area and 2 km in length. A small number of scarp edged collapse sinkholes (up to 7 m in length and 2.5 m in depth) have also been recognised in the floodplain (Gutiérrez-Santolalla *et al.*, 2005b). In a small sector downstream of Zaragoza, Gutiérrez-Santolalla et al. (2005a) found that the dolines show a clear tendency to form clusters. They calculated the spatial distribution index given by the Clark and Evans index (Clark and Evans, 1954). This index quantifies the clustering or dispersion of elements in a particular area. In the La Puebla de Alfindén sinkhole field, the Clark and Evans index has a value close to 0 (R=0.00089), indicating a clustered distribution.

The presence of these dolines causes many problems both in farming activities and civil engineering. Farmers lose arable land and attempt to replace it by filling the depressions each year. In the area upstream of Zaragoza, the problems in civil engineering became very important from the 1970s onwards, when a large number of factories were built. Many buildings were built on depressions which had been filled several years before and no special measures for construction were taken at that time (Soriano and Simón, 1995). Today, the walls and floors of some factories show a high degree of damage due to fracturing (Figure 30 in chapter 3.1.8.).

The surface area occupied by dolines in present air photographs has been reduced with respect to photographs taken in the 50s, due to the filling of voids by the farmers. The farmers fill the depressions with the intention of converting the land into arable production. However, according to some landowners, this is an ineffective practice, as the filled and levelled dolines often remain unproductive due to the fact that they fill the dolines with construction debris in stead of good soils, which are usually more expensive (Gutiérrez-Santolalla *et al*., 2005b).

Downstream of Zaragoza, damage to buildings has been reported in *La Puebla de Alfindén* village. However, in some cases, it is difficult to clarify whether such damage is caused by dissolution subsidence or the collapse of the gypsiferous silts. The *Madrid-Barcelona* motorway (A-2) crosses a few shallow closed subsidence depressions (Gutiérrez-Santolalla *et al*., 2005b).

As to the water management infrastructures, an old section of the *Canal Imperial de Aragón*, the biggest canal in this region, had to be abandoned and rebuilt some meters to the north of the old section, because of several collapses hitting the construction itself (Figure 29).

Some problems can also be observed in *La Cartuja village*. About 15 years ago, the municipal swimming pool was ruptured. In 2003, a doline developed underneath the swimming pool again, probably due to the fact that the suiming pool had been rebuilt without major protective measures 15 years ago.

There are many similar examples that have been collected from previous studies, newspapers and personal meetings with the local inhabitants in the areas. These serve to reassert the importance of this phenomenon and the necessity of a better knowledge of its spatial distribution for a proper land-use management.

5.2.2. Controlling factors

Gutiérrez-Elorza and Gutiérrez-Santolalla (1998) proposed a classification of the factors that play a role in the dissolution process and divided these into geological and environmental factors. On the other hand, Soriano and Simón (1995) distinguished between physical, hydrological and human factors. Despite this difference in classification, their research in the area agree on the main factors that control the subsidence process. These are:

- Geological:
    - i. Lithological: characteristics of the substrate and Quaternary cover (texture, porosity and permeability).
    - ii. Stratigraphical: thickness of gypsum formations and Quaternary cover, intercalation of non-soluble bodies, existence of halite beds.
    - iii. Structural: structure of the gypsum formations, discontinuity plane joints, faults.
    - iv. Geomorphological: relief configuration.
    - v. Hydrogeological: flow velocity and regime, water infiltration, hydraulic gradient, depth and seasonal variations of the water table, thickness of saturated Quaternary deposits, chemical composition of groundwater.

- Environmental:
    - i. Climate: existence of stormy events and high temperatures.

- Anthropogenic factors:
    - i. Irrigation, leakage of canals for irrigation.
    - ii. Pumping.
    - iii. Constructions.

Guerrero *et al.* (2004) reported that recent studies based on borehole data and interpretations of the paleokarst features highlight the relevance of salt and sodium sulphate karstification in the subsidence phenomena. They confirm the presence of halite close to the surface in some locations along the *Huerva* Valley, like *Cadrete* village**.** It seems probable that previously existing halite beds have been removed by dissolution from the outcropping evaporite sequence. The existence of halite and Na-sulphates in the bedrock is a crucial factor for the development of dissolution-induced subsidence phenomena, due to their high solubility. Whereas the solubility of gypsum at 25º C is 2.4 g/l, halite, glauberite and thenardite solubility reach 360, 118 and 519 g/l, respectively (Ford and Williams, 1989).

Guerrero *et al.* (2004) also observed that most of the subsidence problems do not occur inside the city, but in the peripheral areas of Zaragoza, where a relatively thin alluvial mantle can be found. They attribute this to the fact that the majority of the city is built on thickened and slightly cemented alluvial deposits. This affirmation matches with the results obtained by Simón *et al*. (1998b); Soriano and Simón (1995) and Simón *et al.* (1998b). However, a recent study (Gutiérrez- Santolalla *et al.*, 2005b) reveals that, in the Ebro River flood plain downstream of Zaragoza, the alluvium thickness does not have a significant influence on the generation of dolines (see discussion in chapter 7.).

In the study area, two main sets of vertical joints with prevalent N–S and NW–SE directions have been recognised (Arlegui and Simón, 2000). Several authors agree on the high morphogenetic control of the axis NW-SE in the study area. Maldonado *et* *al.* (2000) studied the dolines developed in *La Puebla de Alfindén* village (10 km NE Zaragoza). They discovered that many dolines developed following this NW-SE axis. Besides, Soriano (1992) compared the direction of the axis of dolines with the direction of the fractures, observing a high correlation.

Maldonado *et al*. (2000) also monitored doline evolution and observed that the subsidence activity was controlled by storm events. Soriano and Simón (2002) also reported that subsidence rates correlate with rainfall. However, they affirm that these changes are very subtle, suggesting that the influence of rainfall on doline evolution is not very strong.

Another possible factor may be the location of areas where the Tertiary Aquifer discharges into the Alluvial Aquifer, following the model suggested by Sánche-Navarro *et al.* (2004).

There is a reciprocal interaction between anthropic activities and doline generation. Many infrastructures are affected by subsidence but, at the same time, certain activities favour the generation of dolines. Benito and Gutiérrez-Elorza (1988) observed that dolines preferentially form near unlined canals. Besides, Guerrero *et al*. (2004) observed that the generation of dolines is frequent along the Imperial Canal, particularly on the downgrading side.

Variations in the water table are also other human-induced triggering factor, since the water table changes are mainly caused by irrigation (Soriano and Simón, 1995). As the water level declines, it causes a loss of buoyant support to the ground, increases the flow gradient and velocity, facilitates the aquifer recharge and reduces the geomechanical strength of the cover (Gutiérrez-Elorza and Gutiérrez-Santolalla, 1998).

5.2.3. Dependent and independent variables mapping

The objective of this chapter is to explain the development of the dependent variable (doline/no doline) and the independent variables that will be introduced in the stepwise logistic regression procedure. Due to the lack of information on some factors, such as location of salty layers and fractures in the Tertiary substrate, these models could not be developed (see chapter 3.1.2.). This fact determined the doline probability map accuracy.

Digital Terrain Models (DTM) of the different factors that can be regionalised are created. Digital Terrain Model was defined as “a group of numeric data which describes the spatial distribution of a determined characteristic of the terrain” (Doyle, 1978:1481, in Felicisimo, 1994). Thus, a Digital Elevation Model (DEM) can be considered a kind of Digital Terrain Model.

The models of developed dependent and independent variables have a spatial resolution of 20 m, and are restricted to the Ebro Aquifer, due to the availability of geological and hydrogeological information.

Several methodologies were used for the model development: simple conversion of existing maps into a common reference system or change of data structure (rasterization); in other cases, analysis and digitization of air photographs; finally, the interpolation of punctual data and information modelling, improved, in some case, by the use of 3D modelling for geological information. The utilized software products are ArcGIS 9.1 and Gocad. Figure 51 shows the different steps of the data preparation.

Following this procedure, the information about the dependent and independent variables for each pixel in the DTM was stored in a database and then analysed with a statistical software package, SPSS 11 (SPSS, 2001). In the database, every row corresponds to a case (every location), and the different columns represent the different variables.

ERDAS 8.7 (Leica, 2003) was used for creating the database. This software is capable of importing grids into a same layer stack, which can be exported to ASCII files for easy import into SPSS. SPSS performs the logistic regression analysis and returns the needed logistic regression model parameters in terms of the regression coefficients (see eq. 2). In the final step the model is implemented utilizing the raster calculator in ArcGIS.

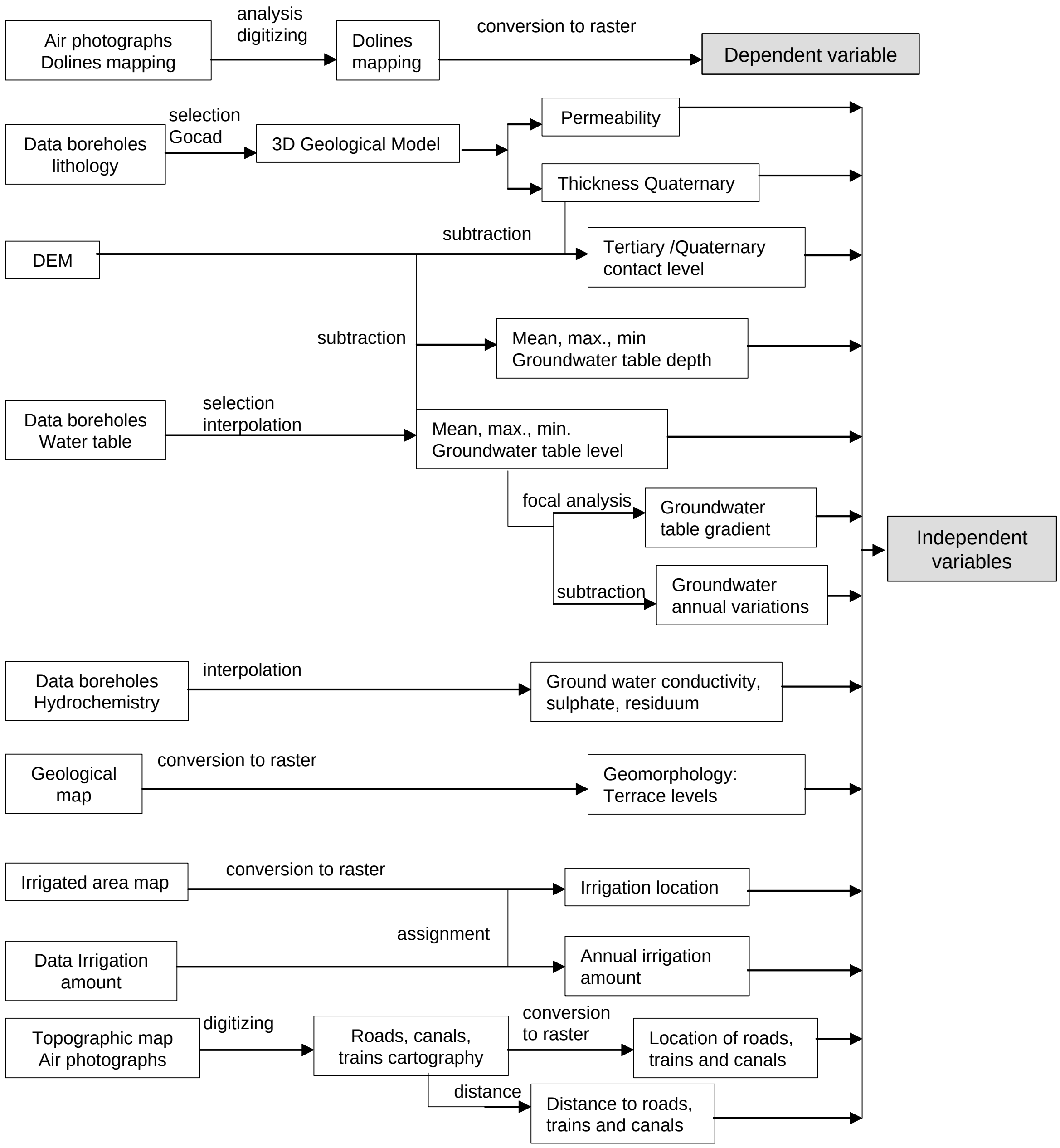


Figure 51: Scheme of the logistic regression variables development.

5.2.3.1. The dependent variable

For the development of the dependent variable doline location, the doline maps of previous studies of the area upstream of Zaragoza were georeferenced and digitalized (Simón *et al.*, 1998a; Simón *et al.*, 1998b). For the areas lacking the appropriate information, air photographs from 1984 and 1997 were analysed. Map 23 shows that doline development is a severe problem in the region along the Ebro Valley. Following this step, the doline vector map was converted into raster format and reclassified into two different values, existence (1) and non-existence (0) of dolines.

5.2.3.2. Geological variables

In the case of the lithological and stratigraphical variables, the 3D model of the Quaternary alluvial deposits of our study area, developed by Oswald Marinoni, was used (see chapter 4.1.). A first attempt was carried out to create a model using only information developed by the Geographical Information System.

Figure 52 shows an example of the thickness of Quaternary deposits model developed in Gocad and ArcGIS 9.1. The data indicates that in the south of *Monzalbarba,* the model developed in the Geographical Information System presents thickness values between 20 and 30 m in a sector where borehole data give values of 30 and 39 m. On the other hand, the Gocad model is better in representing these high thickness values.

In addition, the model performed entirely within the Geographical information system gave an overall map accuracy of 65% and a Kappa index of agreement of 0.31, lower than the 68% of accuracy and 0.36 Kappa index of the final model (see section 5.2.4. for the description of the validation approach).

As a result of these observations, the thickness of Quaternary sediments model and the permeability assessment developed by Oswald Marinoni in Gocad was finally used to perform the logistic regression technique as the introduction of 3D information improved the results reasonably.

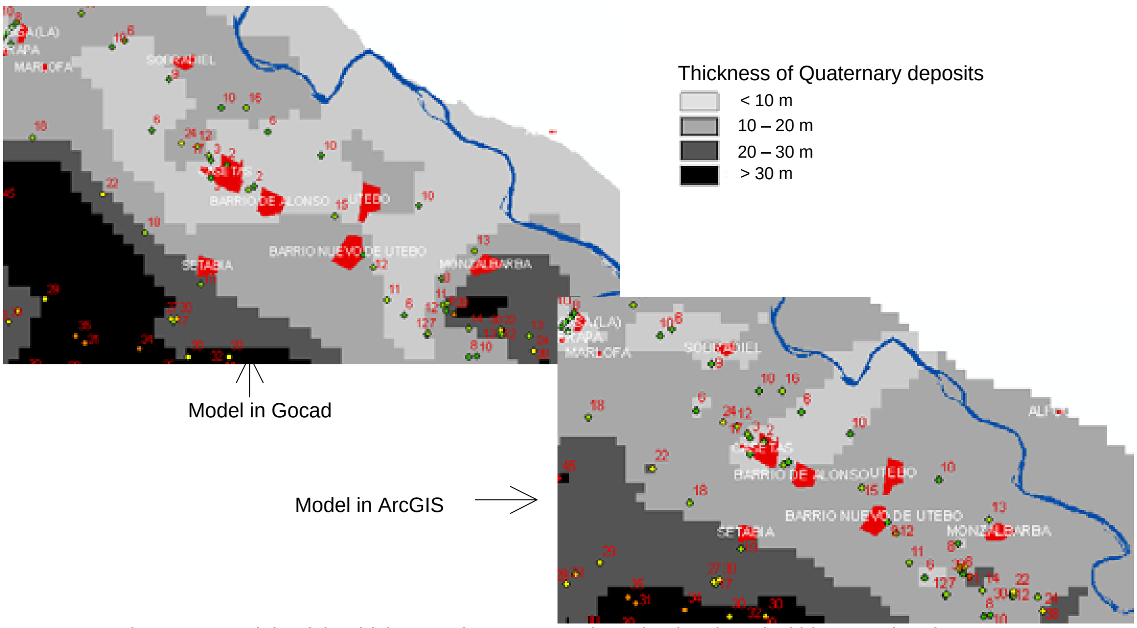


Figure 52: Models of the thickness of Quaternary deposits developed within Gocad and ArcGIS.

The first geological variable to be created was the thickness of Quaternary sediments (Figure 53 and Map 24). For the development of this model, it was very important to collect information from private enterprises, because only a few boreholes in the IPA reached the Tertiary-Quaternary contact (Lamelas et al., 2006a). However, as mentioned in chapter 4.1., the lack of information in the sector downstream of

Zaragoza may reduce the quality of the model in this sector (see chapter 4.1 for the model performance).

In addition, because of the lack of precise information on the permeability of the Quaternary deposits, the permeability of the Quaternary cover was qualitatively assessed by help of the lithological information (Lamelas et al., 2006a). As explained in Lamelas *et al*. (2006) the approach consisted of using the mean grain-size of the Quaternary layers. Clay, silt, sand and gravel represent grain-size classes with sedimentologically well-defined upper and lower grain-size limits, allowing the determination of mean grain size values. In the case of layers consisting of more than one grain-size class, the mean layer grain-size was determined by the proportion of each grain-size class which, in turn, was estimated from the lithological description of the layers. The mean grain-size was then spatially interpolated within the previously modelled 3D body, returning a 3D model of the grain-size. In this model, areas having a mean grain-size value belonging to the clay-silt fraction were categorized as low permeable, whereas the rest were classified as permeable. Finally, the percentage of the column thickness with low permeable layers was extracted to perform a 2D map (Figure 54 and Map 25).

Due to the lack of boreholes in the pediment sector, the model presented unusually low percentage of impermeable layers in a great area covered by glacis, which disagrees with existing knowledge about the permeability of these deposits in the study area. The material which corresponds to the pediments are pebbles in a silt-argillaceous matrix of low permeability. This fact agrees with the results of the model in areas inside the pediments where several boreholes were present. Thus, the model has been improved by assigning the percentage values of low permeable layers found in the glacis to all the area occupied by them (greater than 50%).

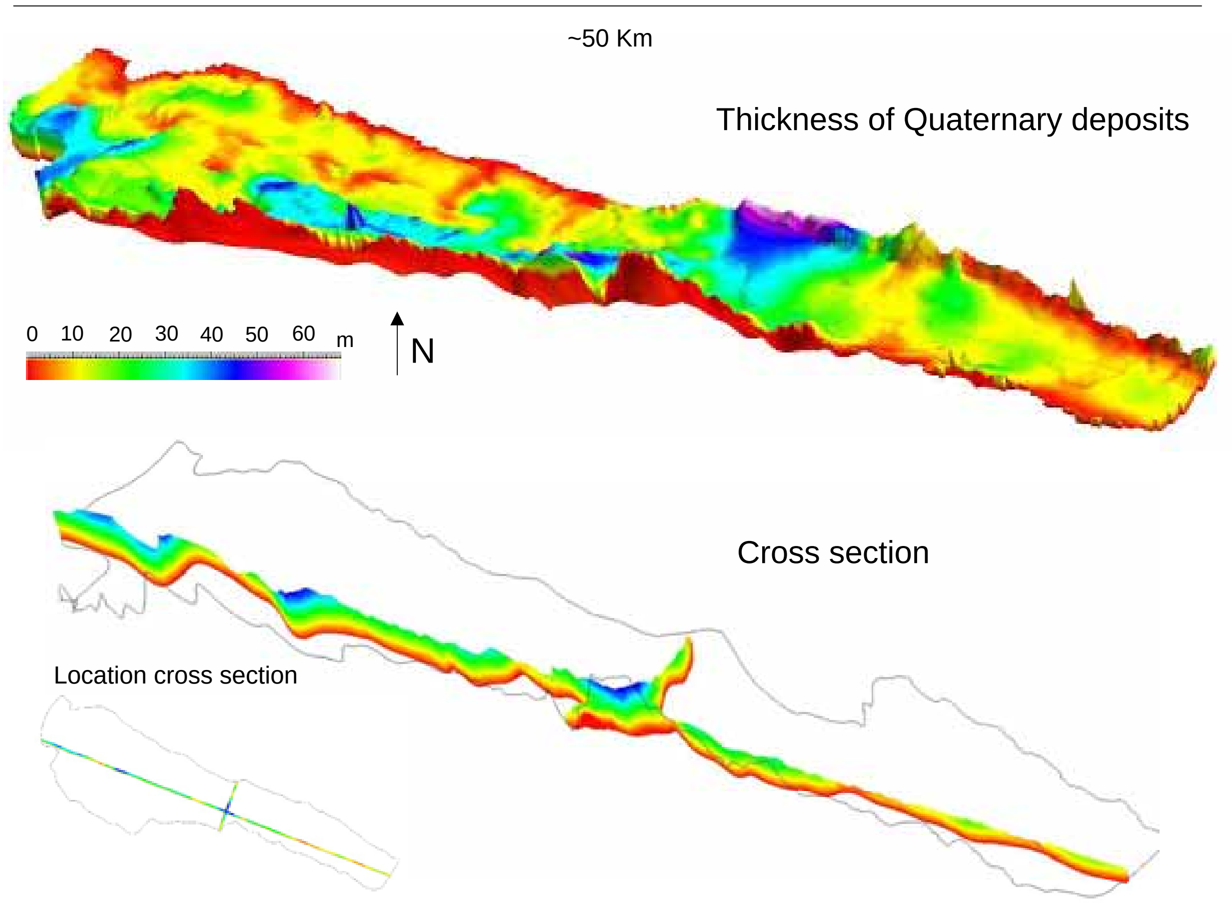


Figure 53: Three dimensional model of the thickness of Quaternary deposits.

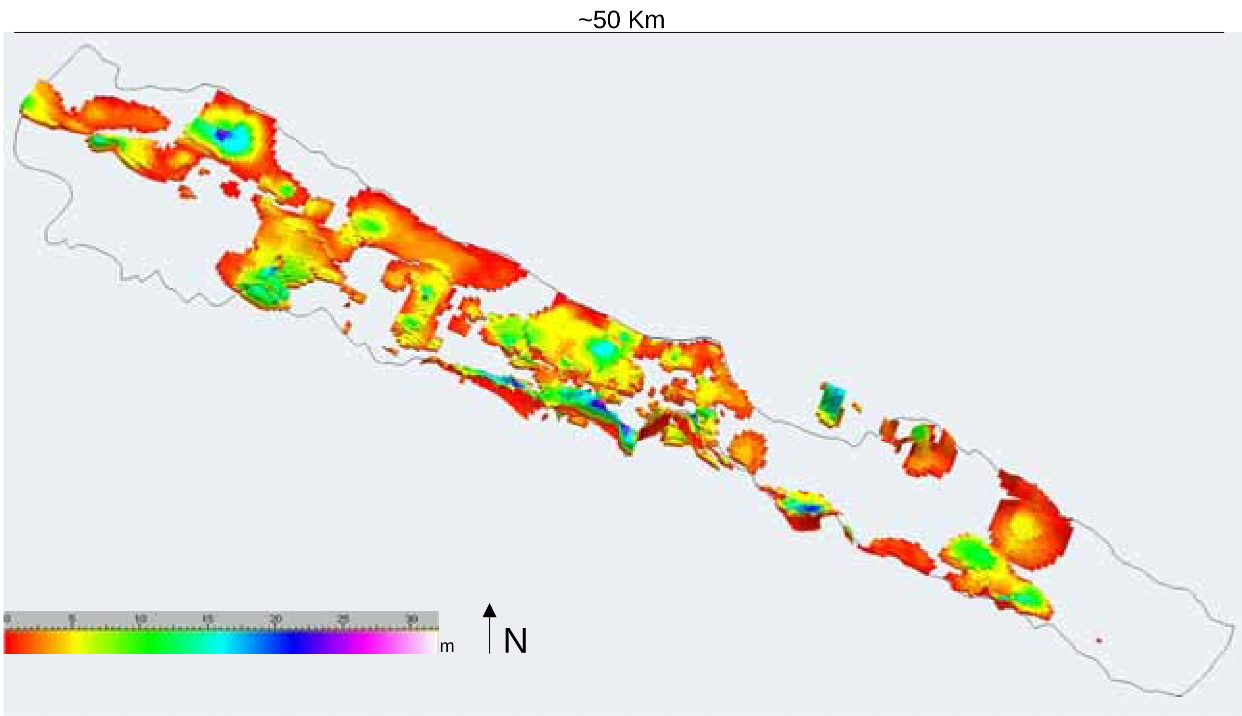


Figure 54: Three-dimensional model of the percentage of low permeable layers.

As to the geomorphology, the geological maps, scale 1:50,000, from the National Geological Institute (ITGE) were used for the location of the different terrace levels. It was our purpose to assess whether doline distribution is linked to a specific terrace level. This information was originally in coverage format from ArcInfo, and had to be converted to raster (Map 2).

Several hydrogeological variables were also developed. The information about water table level and hydrochemistry was also obtained from the IPA. Since this inventory contains all hydrogeological information from different studies, the information is not homogeneous with respect to time and space. Thus, in the case of the water table models, only the points with more than 10 measurements were selected. Maps 26, 27 and 28 show the distribution of the points in the study area with their mean, maximum and minimum water table level values and the models also supported by Oswald Marinoni. The values were extracted from the database and interpolated with ordinary Kriging (Lamelas et al., 2006a).

The groundwater depth models were created by subtraction from the Digital Elevation Model (20 m pixel size) (Map 26, 27, 28). Besides, a subtraction between maximum and minimum water table level models was also carried out for the development of the water table variations between summer and winter. The greatest annual variations are located at the nort-east and south-west of Zaragoza and north of *Alagón* and are mainly explained by the the presence of great thickness of Quaternary deposits (Map 29). The mean water table gradient was created using a focal analysis filter. The standard deviation of a 5x5 pixel kernel was used to model the areas with more water table variations in space, thus implying greater flow velocity (Map 30).

As to the hydrochemistry, of the scarcity of points with several measurements, required the consideration of information from all the boreholes. To avoid the existence of erroneous data, the error balance was calculated according to Custodio and Llamas (1983). After that, all the points with an inadmissible error were rejected. Maps 31,32 and 33 show the location of the boreholes, the conductivity model and the sulphate and dry residue (correponding to the total quantity of salts) content models developed with a simple kriging interpolation technique. The mean values assigned in order to perform the simple Kriging interpolation are 2317.5 mS/cm, 1803.7 mg/l and 13.6 meq/l for conductivity, dry residue and sulfate content respectively.

As in the case of the low percentage of permeable layers model, due to the lack of boreholes in the pediments sector, the models provided unrealistic values for a greater part of the area covered by glacis. Thus, the models were improved by assigning the conductivity, dry residue and sulphate content values found in the boreholes located in the contact between terrace T4 and the glacis to all the area occupied by the pediments.

5.2.3.3. Environmental variables

In the study area, the main environmental triggering factor for doline development is the occurrence of storm events. However, the regression analysis does not include this variable, because, although rainy storms are local phenomena, their number and occurrence is distributed relatively uniform throughout the study area.

5.2.3.4. Anthropogenic variables

The cartography of irrigated areas in 2000, which is available online (http://oph.chebro.es/ContenidoCartoRegadios.htm), was used for the location of irrigated land, as the irrigated land in the alluvial has not changed since 2000. This information, available in coverage format, was converted to raster.

In addition to this, the magnitude of irrigation was approximated using data from a database with information about water resource availability for each agrarian administrative division and irrigation system. More details about the origin of this information can be found in Cruz *et al*. (1997). The map of the irrigation area was intersected with the agrarian administrative division map, also available on the internet, and the values of water availability were assigned to every system in every agrarian division. This is only an approach to the real water supply by irrigation, since the information represents the maximum water availability under regular conditions, but does not take into account dry periods when the real availability is reduced (Map 34).

The infrastructure information was obtained from the digital topographic map, scale 1:25,000, from the National Geographical Institute (IGN). The information, originally in CAD format, had to be previously transformed to ArcGIS format (work performed by José Angel Losada, from CHE), and later updated with the cartography of new roads and trains constructed after the topographic map creation. More recent air photographs and cartographies from Zaragoza Council were analysed and digitalized for this purpose (Map 4). Models representing the distance to these infrastructures were also performed, as it was believed that the occurrence of dolines could increase proportionally to the distance of some infrastructures. A distance operation into ArcGIS was carried out for the development of these models.

5.2.4. Selection of the model

In order to improve knowledge of the factors controlling doline distribution, the models of the different factors were visually analysed, together with the cartography of dolines. In addition, a first analysis of the correlation of the continuos variables with the density of dolines was performed. Table 43 shows the values of these correlations, which are significant at the 0.01 level. The highest correlation values were obtained by hydrogeolocal factors, *i.e.* water table gradient, annual groundwater variations and groundwater conductivity, and the elevation of the contact Tertiary/Quaternary (COTA_Q) .

A multiple linear regression analysis was also carried out between doline density and the factors with higher correlation. However, the result was not satisfactory producing an adjusted R square of 0.396. Therefore, it was definitively decided to perform a logistic regression technique.

Table 43: Pearson correlation between the continuos factors and the density of dolines.

Factors	Name	Pearson correlation
Lithological		
Percentage of impermeable layers in Quaternary	PERMEABI	-0.087
Stratigraphical		
Thickness of Quaternary deposits	Q_DEP	-0.031
Elevation of Quaternary deposits	COTA_Q	0.317
Hydrogeological		
Groundwater table mean depth	MEAWTDEP	-0.168
Groundwater table minimum depth	HIGWTDEP	-0.185
Groundwater table maximum depth	LOWTDEP	-0.085
Watertable mean level	WT_MEAN	0.410
Watertable low level	WT_LOW	0.390
Watertable high level	WT_HIGH	0.410
Watertable gradient	GRAWTMEA	0.488
Annual groundwater table variations	WT_VARIA	0.448
Groundwater conductivity	CONDU	-0.308
Groundwater content of sulphates	SULPHATE	-0.241
Groundwater content of residuum	RESID	-0.248
Anthropogenic		
Distance to canals	DIS_CAN	-0.164
Distance to roads	DIS_ROAD	-0.126
Distance to trains	DIS_TRAIN	-0.164

The logistic regression techniques allows the introduction of categorical variables. Thus, some of the variables were classified into different categories taking into account previous studies and the visual analysis. Both variables, the continuous and the categorical, were introduced in the analysis. Table 44 shows the different variables introduced in the model and their continuous or categorical condition.

A subset of 60% of the total information, randomly selected, was introduced in a stepwise logistic regression procedure. The other 40 % of information was retained in order to validate the model. A stepwise selection method was performed. In this method variables are introduced one by one based on the significance of the score statistic, and removed based on the probability of a likelihood-ratio statistic, based on conditional parameter estimates. Table 44 shows the total score statistic previous to the introduction of the variables in the stepwise procedure. The watertable gradient presented the highest total score therefore being the first one introduced in the model. The total score statistic is recalculated after every step in order to select the next variable to be introduced in the model.

Table 44: Variables introduced in the logistic regression and total score statistic previous to the stepwise procedure.

Factors	Name	Type	Total score
Lithological			
Percentage of impermeable layers in Quaternary	PERMEABI	Continuous	348.14
Percentage of impermeable layers in Quaternary 0-10 %	PERME_10(1)	Categorical	214.57
Percentage of impermeable layers in Quaternary >10 %	PERME_100(1)	Categorical	150.00
Stratigraphical			
Thickness of Quaternary deposits 0-15 m	DEPQ_15(1)	Categorical	82.15
Thickness of Quaternary deposits 15-30 m	DEPQ_30(1)	Categorical	9.79
Thickness of Quaternary deposits >30 m	DEPQ_80(1)	Categorical	381.26
Thickness of Quaternary deposits	Q_DEP	Continuous	270.57
Elevation of Quaternary deposits	COTA_Q	Continuous	2166.49
Geomorphological			
Geomorphology. Terrace level T4	T4(1)	Categorical	20.88
Geomorphology. Terrace level T3	T3(1)	Categorical	1431.22
Geomorphology. Terrace level T2	T2(1)	Categorical	4213.82
Geomorphology. Terrace level T1	T1(1)	Categorical	3034.58
Geomorphology. Endorheic area	GEOENDOR(1)	Categorical	2556.96
Hydrogeological			
Groundwater table mean depth	MEAWTDEP	Continuous	1398.31
Groundwater table minimum depth	HIGWTDEP	Continuous	1773.94
Groundwater table maximum depth	LOWTDEP	Continuous	665.18
Watertable mean level	WT_MEAN	Continuous	3420.06
Watertable low level	WT_LOW	Continuous	3050.00
Watertable high level	WT_HIGH	Continuous	3432.54
Watertable gradient	GRAWTMEA	Continuous	6101.85
Annual groundwater table variations	WT_VARIA	Continuous	4783.12
Groundwater conductivity	CONDU	Continuous	2006.10
Groundwater content of sulphates	SULPHATE	Continuous	959.71
Groundwater content of residuum	RESID	Continuous	887.97
Anthropogenic			
Irrigation location	IRRIG_CL(1)	Categorical	884.53
Distance to canals	DIS_CAN	Continuous	330.88
Distance to roads	DIS_ROAD	Continuous	271.51
Distance to trains	DIS_TRAIN	Continuous	330.88
Location of canals	CANAL(1)	Categorical	31.43
Location of trains	TRAIN(1)	Categorical	42.37
Location of roads	ROAD(1)	Categorical	55.00

The fitness of the logistic regression equation was tested using this 60% sample data. As mentioned in chapter 5.2., the coefficient of determination (r^2) frequently used in linear regression has little meaning in logistic regreession. Thus, for the overall model fit the goodness-of-fit test, called “chi-square” in SPSS, was used. This test is simply the chi-square difference between the null model (*i.e.* with the constant only) and the model containing one or more predictors. This is one application of the likelihood ratio test between two nested models. It is an assessment of the improvement of fit between the predicted and the observed values by adding the predictor(s). Also, a classification table of observed dolines (0 and 1) and adjusted probability classes (determining a dividing point by matching the quantity of the number of 1s in the observed values of the dependent variable) to obtain the overall percentage of correct classifications was performed.

In the final model, a total of 11 variables were introduced (or used): eight categorical and three continuous variables. Table 45 shows the variables introduced in the model. β represents the coefficients of the logistic equation. The Wald test is usually used to test the significance of a single predictor. It tests the hypothesis that the predictor is useful in predicting the outcome. In this case, all the variables are significant ($\alpha < 0.05$) since the method used has been a stepwise procedure. And finally, the exp. of β is the change in odds for a unit increase in the independent variable. This last statistic shows the relative importance of the variables.

According to this, the most significant variable is geomorphology, represented, in order of importance, by the location of endorheic areas and different terrace levels, T4, T3, T2 and T1. It is followed by the presence of irrigation and the water table gradient.

Table 45: Variables introduced into the model.

Factors	**β**	**Wald**	**Exp(β)**
HIGWTDEP	-0.09	1682.69	0.92
SULPHATE	-0.02	204.05	0.98
T4(1)	2.35	1714.70	10.50
T3(1)	2.04	1425.65	7.68
T2(1)	1.71	1342.72	5.53
T1(1)	0.57	151.92	1.77
GEOENDOR(1	2.33	1372.01	10.26
DEPQ_80(1)	-0.64	309.93	0.53
IRRIG_CL(1)	0.48	269.61	1.61
PERME_10(1)	0.14	66.31	1.15
GRAWTMEA	0.33	167.38	1.39
Constant	-4.08	5579.57	0.02

The next most important variable is the percentage of low permeable layers in the Quaternary cover. According to the model, it only plays a role when it is classified into two categories. Thus, the existence of low percentage, less than 10%, of low permeable (impermeable) layers increases the doline probability, in accordance with the positive value of its coefficient.

The factors with negative coefficients are the ones of less importance in this case, due to their low exp. of β. The results suggest that the areas with the highest groundwater sulphate content reduce doline probability. Besides, doline probability increases in areas with lower summer water table depth -which implies an increased supply through irrigation. Finally, doline probability is also reduced in areas where the Quaternary depth is more than 30 m thick.

The variables selected by the model represent the doline distribution in the study area. However, this does not imply that they are the sole contributors towards a hazard development. An example is the water table variations. This variable is very important and is highly correlated with doline density (see Table 43) and high total score statistic (see Table 44). However, this factor is not introduced in the model because of its high correlation (0.710) with the water table gradient, which implies a reduction in its total score statistic (550 total score) when the groundwater table gradient factor is introduced in the model. As a consequence, in the second step of the stepwise procedure, the location of terrace T2 (with total score of 1886) is introduced in the model.

The determined model was validated with the 40% of information not introduced in the logistic regression, by comparing the predicted outcome (probability value) with the reality (dolines occurrence or not). Due to the difference in percentage between the two groups (existence or not of dolines), and the difficulty in understanding the validation results, all doline incidences, and 12,000 points where dolines were not present (selected at random), were selected making a total validation sample of 24,059 cases. The resulting confusion (error) matrix (Table 46) yields an overall map accuracy of more than 68% and a Kappa index of agreement of 0.36. This means that the agreement of this classification is 36% better than that obtained just by chance. The confusion matrix is commonly used in classificatory approaches as a way to test the model performance (Beguería and Lorente, 2003; Martínez-Casanovas *et al*., 2004).

Table 46: Confusion matrix.

		Predicted			
		0	**1**	**total**	**Correct %**
Observed	**0**	8823	3177	12000	73.53
	1	4477	7582	12059	62.38
	Total	13300	10759	24059	68.19

Logistic models are frequently used in a classification approach. This implies selecting given values of the response variable and classifying all the cells in one of the groups formed according to these. The method more commonly adopted in literature is to divide the histogram of the probability map into different categories based on expert options (Dai and Lee, 2002; Lee and Min, 2001; Ohlmacher and Davis, 2003). In the case of division into two groups, the threshold value is normally a 0.5 probability, since the two sample groups are usually similar in size. For the case where the two groups are very dissimilar, the proportion of ones in the sample (proportion of dolines, 0.06 in our study area) can be used instead of the 0.5 value (Beguería and Lorente, 2003; Martínez-Casanovas *et al*., 2004). According to Ayalew and Yamagishi (2005), this type of changing continuous data into two or more categories does not take into account the relative position of a case within the probability map, and is neither fully automated, nor statistically tested. They suggested classification systems that use quantiles, natural breaks, equal intervals and standard deviation to choose the one that best suits the information and the scale of investigation.

Map 35 shows the doline probability map and, superimposed, the location of dolines, since they have to be considered as areas with a higher probability of doline development. In this case, the map has been classified in four categories, using the mean and standard deviation values. It should be noted that the division into categories is intended for visualization purposes only and does not imply a categorization into safe and unsafe areas. In fact, all the covered karst area in particular, and our study area in general, present a certain high probability of doline development.

The highest susceptibility values are generally present in the terrace T2, over the whole study area, and in the contact area between T2 and T4, in the sector upstream of Zaragoza, with the exception of the areas with thick Quaternary deposits (usually greater than 30 m), which produce low susceptibility values. This last situation occurs in a sector north-east of Zaragoza city and within the city, where traditionally high thickness of Quaternary sediments has been assumed. Also, an area upstream of the mouth of the *Jalón* River shows low susceptibility values, due to the thick Quaternary deposits, although it is located in terrace T2.

In addition to areas with thick Quaternary deposits, the lower susceptibility values are also located in areas with higher percentage of impermeable layers. This is the case in terrace T1 upstream of Zaragoza, the surroundings of *Alagón* city and the south of Zaragoza.

The low susceptibility areas also correspond to areas where there is no irrigation, with the exception of the *Logroño* road (upstream of Zaragoza), which presents high susceptibility values. This may be explained by the transformation which this area suffered in the 60s and 70s, due to the industrialization process. It was traditionally a wetland with many shallow depressions used for irrigated agriculture.

5.3. Groundwater vulnerability

As mentioned in section 2.3.3.5. the method developed by the German State Geological Surveys is applied in order to assess groundwater vulnerability. The basic idea of this method, developed by Hölting *et al*. (1995), is that the effectiveness of all natural processes in the protective cover for reducing contaminant concentration is mainly dependent on travel time. As a consequence, the protective function depends on the main factors which control travel time: the thickness of each stratum and the properties of the materials (Goldscheider *et al*., 2000). In relation to this fact, the protective function of the upper soil is assessed according to the effective field capacity (*B* value).

The protective function of the subsoil is obtained as follows: the value for the protective function of each stratum above the water table (*G* value) is multiplied by the thickness of that stratum (*M* value). Afterwards, the protective values of the soil and subsoil are added and multiplied by a factor reflecting the amount of recharge (*W* value), as the following formula shows:

$$S = (B + (\sum M*G))*W \qquad (4)$$

An additional protective function term may be included for artesian conditions and for a perched aquifer above the aquifer in question. These conditions are not present in the study area, and therefore, these two factors are not included in the model.

The final value is called “protective function, total score”. It might be any possible value. The final values are classified into five classes, from very low to very high protection, based on experience (Table 47).

Table 47: Classification of protective function total scores.

Protective function	Total score
Very high	> 4000
High	2000-4000
Medium	1000-2000
Low	500-1000
Very low	< 500

It was also our purpose to compare the results of applying this model completely in ArcGIS 9.1, or using the 3D software, Gocad. Thus, two approaches were developed; the first one developed by myself with ArcGIS; the second, developed by Oswald Marinoni within Gocad (Lamelas *et al.*, 2007).

In the GLA method the recharge can be estimated from precipitation and evapotranspiration values, but in the study area annual evapotranspiration exceeds annual precipitation, so the annual recharge of the aquifer is highly influenced by irrigation water. As a consequence, two vulnerability maps were developed, one taking into consideration the irrigation amount, and the other only including the natural conditions of the area. This process was performed twice: inside ArcGIS 9.1 and Gocad, resulting in 4 different models.

The basic difference between the groundwater vulnerability assessment based on the Geographical Information System and the solution provided with Gocad is that the latter takes full advantage of the three dimensions of the subsurface. However, there are some aspects that must be performed within the Geographical Information System, which are then introduced in the Gocad process at a later stage. These aspects are the protective function of the upper soil (*B* value), the amount of recharge (*W* value) and the water table model. The first part of this chapter explains the development process of these three models. This is followed by a detailed discussion of the groundwater vulnerability maps developed within the Geographical Information System and Gocad.

5.3.1. The protective function of the upper soil: the *B* value

The information from the MicroLEIS system (de la Rosa and Magaldi, 1982) was used for assessing the effective field capacity of the soil. This system includes a relationship between different textures of the soils and field capacities.

The information about the texture of the different morpho-edaphic units was available in previous studies, so it was possible to assign the field capacity to the different types of soils. Table 48 shows the different morpho-edaphic units with their effective field capacity and corresponding *B* value. For the regionalisation of these values see Map 36.

Table 48: Hölting et al. (1995) *B* value for the different types of soil.

Soils/Properties	Effective field capacity mm/m	B value
Haplic Gypsisols	225,2	500
Calcaric Cambisols	190,4	250
Petric Calcisols	190,4	250
Haplic Solonchaks	146,8	250
Calcaric Fluvisols	120,3	125
Calcaric Regosols	190,4	250

5.3.2. The amount of recharge: the *W* value

Precipitation and evapotranspiration models for the study area were developed by utilizing information from the National Meteorological Institute (INM, *Instituto Nacional de Meteorología*). This information belongs to a series of 50-year data, from 1940 to 1990, filled by means of one of the most complex, feasible and strict methods for monthly data analysis and fill, Monthly Streamflow Simulation Computer Program, developed by the Hydrologic Engineering Centre, from the Corps of Engineers in USA, commonly known as MOSS-IV (M.O.P.T., 1993, 1996). This covers the requirements of the W.M.O. (World Meteorological Organization) that determines a minimum of a 30-year period of measurements for characterizing a climatic variable as precipitation and evapotranspiration (W.M.O., 1967). The evapotranspiration data were obtained using the Thornthwaite method (Thornthwaite, 1948), which only requires data about the mean monthly temperature for the calculation.

Following this, the information will be interpolated in order to obtain a continuous surface for the project area. Here, the scarcity of climatic stations with long-period data (9 and 7 for evapotranspiration and precipitation respectively) and their heterogeneous distribution within the study area (see Map 37) proved to be a handicap for the regionalisation of the meteorological data. The solution to this problem is provided by enlarging the area to be interpolated (with 27 and 51 evapotranspiration and precipitation stations respectively) and using a global methodology, a multiple regression analysis between the meteorological variables and continuous geographical variables (altitude, latitude, continentality, solar radiation).

This deterministic method used by several authors (Ninyerola *et al*., 2000, 2005; Vicente and Saz-Sánchez, 2002) may be appreciated as an alternative to classical interpolation techniques, when spatial information is available. In this case, the following spatial information was chosen: altitude extracted from the Digital Elevation Model of 20 m spatial resolution (M.A.P.A., 1997), latitude represented by the y coordinate, longitude represented by the x coordinate, continentality represented by the distance to Mediterranean and Cantabric Seas and, finally, only in the case of the evapotranspiration, the solar radiation. These factors were introduced in a multiple regression analysis using a stepwise method.

After verifying all the assumptions of a multiple regression (normality, linearity and homocedasticity) and applying the subsequent transformations to the data, the distance to Mediterranean Sea and the elevation above sea level were the two variables introduced in both precipitation and evapotranspiration models. Afterwards, both models were performed in ArcGIS calculator to obtain the final precipitation and evapotranspiration continuous surfaces (Map 38, 39).

Under natural conditions (without irrigation), since precipitation is lower than evapotranspiration, the whole area reaches the highest *W* value, implying high protection. However, for the recharge under irrigation conditions, the approximation to the irrigation amount performed for the dolines susceptibility model was also added. It should be noted that this is only an approach to the real water supply by irrigation, as it shows the maximum water availability under regular conditions without taking the dry periods into account.

Maps 40 and 41 show the recharge values after adding precipitation and irrigation and subtracting evapotranspiration and the W value for the model, taking irrigation into account.

5.3.3. The water table model

For the determination of the unsaturated zone, a model of the water table is needed, so that the layers that are going to take part in the protective function can be specified. The mean (irrigation conditions) and minimum (without irrigation) water table level models developed for the doline susceptibility model by Oswald Marinoni (see chapter 5.2.3.2.) were used to determine the unsaturated zone (Maps 26 and 28).

5.3.4. The Groundwater vulnerability within the Geographical Information System

Figure 55 shows a sketch of the working steps within the Geographical Information System. First of all, two maps must be developed: the protective function of the soil (*B* value) and subsoil (*M*G* value), respectively. Then, both maps are added with the raster calculator in ArcGIS. Afterwards, the result is multiplied by the aquifer recharge mapping (*W* value), created by following Formula 4.

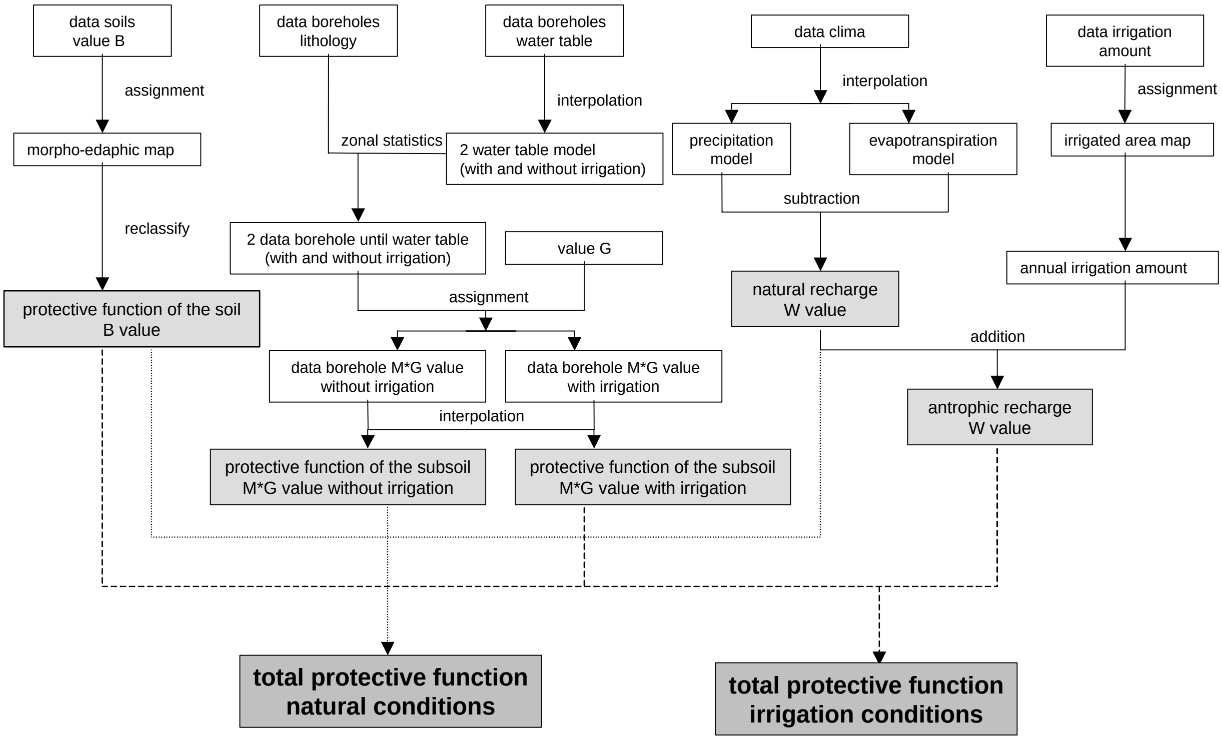


Figure 55: Scheme of the groundwater vulnerability model (after Hölting *et al*., 1995), developed within the Geographical Information System.

Consequently, the protective function of the subsoil in the unsaturated zone must be calculated for the development of the model within the Geographical Information System. The unsaturated zone subsoil, consisting of granular, non-lithified material, is the layer below the topsoil and above the water table. The protective function is calculated according to its grain-size distribution, which is also related to permeability, and thickness (*M*G* value). The subsoil information for the model development is the same as that used for the construction of the 3D geological model (see chapter 4.1.).

Table 49 shows the different protective values assigned to different descriptions of subsoil stratum. The protective function of every borehole is calculated, as explained before, by multiplying the protective function of every stratum by its thickness and summing up all the strata values above the water table. This value needs double calculation, since the water table varies from natural conditions (that is, without taking irrigation into account) to anthropologic and actual conditions (taking irrigation into account).

Afterwards, the protective values of the subsoils in the boreholes are interpolated. In this case, a simple kriging interpolation within the Geographical Information System has been applied to obtain two continuous surfaces, one taking irrigation water into account and another under natural conditions without irrigation (Maps 42 and 43). The mean value introduced in the simple kriging interpolation were 1314.1 and 994.1 for the model without irrigation and with irrigation respectively.

The final groundwater vulnerability models after applying Formula 4 are shown in Maps 44 and 45. The doline mapping is superimposed and receives the lower values of protection in order to take into account the special characteristics of karst (see chapter 2.3.3.5.), following the recommendation by Goldsheider *et al*. (2000). These areas are usually in direct contact with the aquifer and, as a consequence, are more vulnerable to ground water contamination.

In the case of groundwater vulnerability with irrigation, the model is highly determined by the water recharge. Thus, the highest vulnerability values are located in the lower terraces with irrigation land use. There are some exceptions, *i.e.* the surroundings of the *Virgen de la Columna* urbanization (*El Burgo de Ebro* municipality), the north-west of Zaragoza and the north of *Alagón,* where medium or low susceptibility values appear, although irrigation is present. This usually occurs because of high protection values of the subsoil, caused by thick unsaturated Quaternary sediments or high occurence of impermeable layers in the lithological profile.

The values of protection improve considerably in the case of the model under natural condition without application of water by irrigation. This model follows much more clearly the tendency of the protective function of the subsoil, but with the added circumstance of improving the values of protection, since, in the whole area, the protective function of the subsoil is multiplied by 1.5 (due to the low recharge). Thus, here again, the highest protective values are located in areas with higher thickness of unsaturated Quaternary sediments or areas with high percentage of impermeable layers in the profile. It is remarkable the situation in the north-east of Zaragoza, where relatively high thickness of unsaturated sediments is present, but the vulnerability is high, due to the elevated permeability of the layers.

As in the case of the permeability, the model presented unusually low protective values in the pediment sector, due to lack of information. This disagrees with the protective values of the few borehole found there, *i.e.* borehole number 821 and 963 (Map 42, 43). Thus, the model was modified in the pediment sector. A calculation of an estimated protective value, developed with the original borehole data, was performed.

The strata found in the glacis correspond to the descriptions *L, LG, LKG, LY, LA, LAG, LK,GL, ALK* and *GAL* (Table 49). The G values assigned to these lithologies, according to Hölting *et al*. (1995), are: 75, 100, 170, 200 and 500. Consequently, the average mean value 150 was selected as representative of the whole pediment sector.

In addition, an average thickness of 15 m was also selected, and, finally, equation 5 was twice performed:

Under natural conditions: (250+ (14*150))*1.5 = 3525

Under irrigation conditions: (250+ (14*150))*0.5 = 1175

As a result, a high groundwater protection under natural conditions, value 3525, was assigned to all the pediments sector. In actual conditions, the same value was assigned to the majority of the glacis extension. Nevertheless, in the irrigated areas, the value 1175, medium groundwater protection, was selected.

Table 49: *G* value according to Hölting *et al*. (1995) for different stratum description. *A*= sand, *G*= gravel, *C*= conglomerates, *L*= clay, *M*= marls, *Y*= gypsum, *K*= limestone, *D*= dolomite, *H*= halite, *P*= schist, *S*= soil, *R*= fillings, *?*= unknown, *V*= cavity, *DY*= debris.

Description boreholes	G value	Description boreholes	G value	Description boreholes	G value	Description boreholes	G value
R	8	V	0	A	25	L,M	100
C	5	K	5	A,G	10	L,M,Y	100
C,G,Y	5	K,M	5	A,G,C	10	L,A	170
C,L	75	K,L	5	A,G,L	75	L,A,G	100
C,Y	5	M	20	A,G,Y	10	L,Y	200
D,Y	5	M,G	20	A,L	75	L,Y,M	200
G	5	M,K	20	A,L,G	75	Y	5
G,M	50	M,A	20	A,L,K	75	Y,C	5
G,A	10	M,L	20	A,Y	25	Y,G	5
G,A,M	60	M,L,Y	20	L	500	Y,M	5
G,A,L	75	M,Y	20	L,G	100	Y,H	5
G,A,Y	10	M,Y,L	20	L,G,K	100	Y,L	5
G,L	75	S	1	L,K	100	Y,L,M	5
G,L,A	75	?	1	L,K,G	100		

5.3.5. The groundwater vulnerability in Gocad

As explained in chapter 4.1., the preparation of a three-dimensional object requires more effort in terms of considering a variety of geometric boundary conditions. The geological body to be considered, the unsaturated zone, must be filled with the information necessary for model development. As a consequence, in our project, the layers encountered in the boreholes were assigned with a G value, determined by Hölting *et al*. (1995), which represents the properties of the material which reduce contaminants arriving at the groundwater (Table 49) taken from Table 49 (*G*-value). These *G*-values were then interpolated within the sGrid object, in order to fill the 3D space (Lamelas *et al*., 2007) .

In addition, the *G* value property, an sGrid object can include various other properties. This makes it possible to keep all information required for the groundwater vulnerability calculation in one object. As a consequence, additional properties (*B, W* values developed with the Geographical Information System) were added to the sGrid. Moreover, other properties were introduced which helped to distinguish between different areas. For instance, a Boolean property was added, which distinguishes between layers above and below the groundwater table. All the cells of the sGrid above the groundwater table were given a value of 1, whereas the rest were given a value of 0 (Lamelas *et al.*, 2007).

Finally, a script was applied on the sGrid, allowing a user defined computation of the protective function for each column of the sGrid. Figure 56 shows the principle of the computations, where a groundwater recharge between 300-400 mm/a (*W*=1) is assumed. The resulting value for each column was projected as a point on a flat 2D surface. This collection of points was then imported by ArcGIS and transformed to a map representing the protective function of the unsaturated zone or the groundwater vulnerability, respectively (Lamelas et al., 2007).

Similar problems to the ones in the ArcGIS model were found in the Gocad model in the pediment sector (see chapter 5.3.4.). Consequently, the approach applied to the models developed in the Geographical Information System was performed for the Gocad models in the pediment sector.

The groundwater vulnerability with irrigation conditions model is also extremely influenced by the recharge, as in the case of the model generated in ArcGIS. But, within Gocad, this influence is highly smoothed by the 3D interpolation method.

In general, both results follow the same general tendency, however, the model developed in ArcGIS presents lower protection values in some sectors where, according to the Gocad model, the protection class is medium or even high. This is the case of the meander at the south of *Juslibol*. This sector presents relatively high thickness of Quaternary deposits (see Maps 24, thickness of Quaternary deposits), high thickness of unsaturated materials (see Map 26, mean depth of water table level respectively) and a high percentage of impermeable layers (see Map 25). Thus, for these sectors the Gocad model provides more reliable protection values according to the characteristics of the aquifer. Similar cases can be observed *i.e.* east of *Garrapinillos,* north east of *Alagón* in the confluence of the *Jalón* and Ebro Rivers and in the surroundings of *La Cartuja.*

Greater differences are observed between the model developed under natural conditions with Gocad and the one developed with ArcGIS. The latter tends to exaggerate the protection in the lowest values of protection, and reduce the protection in the highest values. An example of this situation can be observed in the right bank of the Ebro River downstream of El *Burgo de Ebro*. This sector, has thin unsaturated deposits and a low percentage of impermeable layers. This would imply very low protection values, as the Gocad model suggests. However, the ArcGIS model provides medium and high protection values.

As mentioned above, according to some characteristics of the aquifer, the Gocad models present, in general, more reliable protective values. Besides, this model present smoother results, which match the continuous condition of natural phenomena. In addition, the reconstruction of the geometry of the Quaternary deposits improved with the use of three-dimensional approaches (see chapter chapter 5.2.3.2.). Thus, when feasible, it is recommended to perform 3D approaches, although they are frequently more time and money consuming. As a consequence of these results Gocad developed models will be used in the land-use suitability analysis.

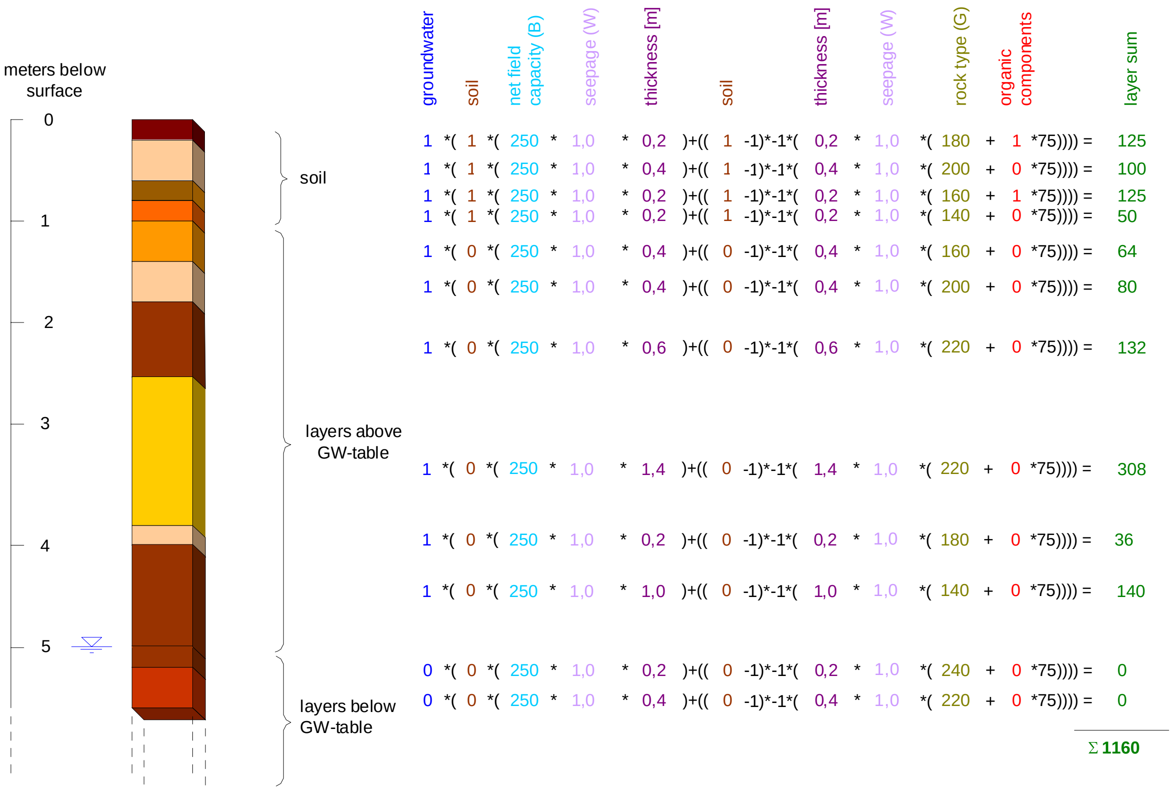


Figure 56: Example calculation for one column of an sGrid object. According to table 1, a value of 1160 is equal to a medium protective function of the unsaturated zone (slightly modified by Oswald Marinoni after Lerch, 2005).

6. Land-use suitability analysis

In this chapter the land-use suitability analysis is presented. Three approaches have been developed. First, a site search analysis, developed with the *Simple Additive Weighting* method and the *Analytical Hierarchy Process* integrated in ArcGIS (see chapter 2.3.4.) for the creation of suitability maps for the different land-uses analysed in this project. These are:

- Sand and gravel extractions.
- Irrigation areas.
- Industrial settlements.
- Urban constructions.

Secondly, a site selection analysis for the same land uses, developed with the *PROMETHEE-2* methodology also integrated in a Geographical Information System (see chapter 2.3.4.).

Finally, the control of the uncertainty of the values in the input data will be improved with the application of the stochastic *PROMETHEE-2* and *Montecarlo simulation* (see chapter 2.3.4.).

As cited in chapter 2.3.4., all MultiCriteria Decision-Making (MCDM) methods have certain aspects in common. Alternatives represent the different choices of action available to the decision maker. Multiple attributes represent the lowest level of decision criteria. Decision weights are assigned to the attributes. Usually, these weights are normalized to add up to one.

Thus, several steps must be covered in the suitability analysis. They are:

- Definition of alternatives: in the case of site search analysis every pixel represents one alternative, so alternatives are already defined.
- Definition of constraints: areas with land-use restrictions.
- Definition of variables: factors that play a role in the decision process and should be considered.
- Transformation into criteria: standardization of variables. In the case of *PROMETHEE-2* and stochastic *PROMETHEE-2*, standardization is not necessary, due to their outranking nature.
- Assignment of decision weights: in our case, with the use of *Analytical Hierarchy Process*.

6.1. Site search analysis

The final result of the site search analysis is the development of suitability maps for the location of new land uses (Figure 57). As every pixel represents one alternative, the final map shows a ranking of all the pixels in the map and presents a continuous surface, which shows different suitability ranges. The integration of *Simple Additive Weighting* method and *Analytical Hierarchy Process* in a Geographical Information System is a valuable tool for this purpose. *Simple Additive Weighting* methods are the most commonly used techniques for tackling spatial multiattribute decision making in Geographical Information Systems, since their application is extremely easy (see chapter 2.3.4.). Besides, the *Analytical Hierarchy Process* can be employed to derive the weights associated with suitability (attribute) map layers. Then, these weights can be combined with the attribute map layers in a way similar to the linear additive combination methods.

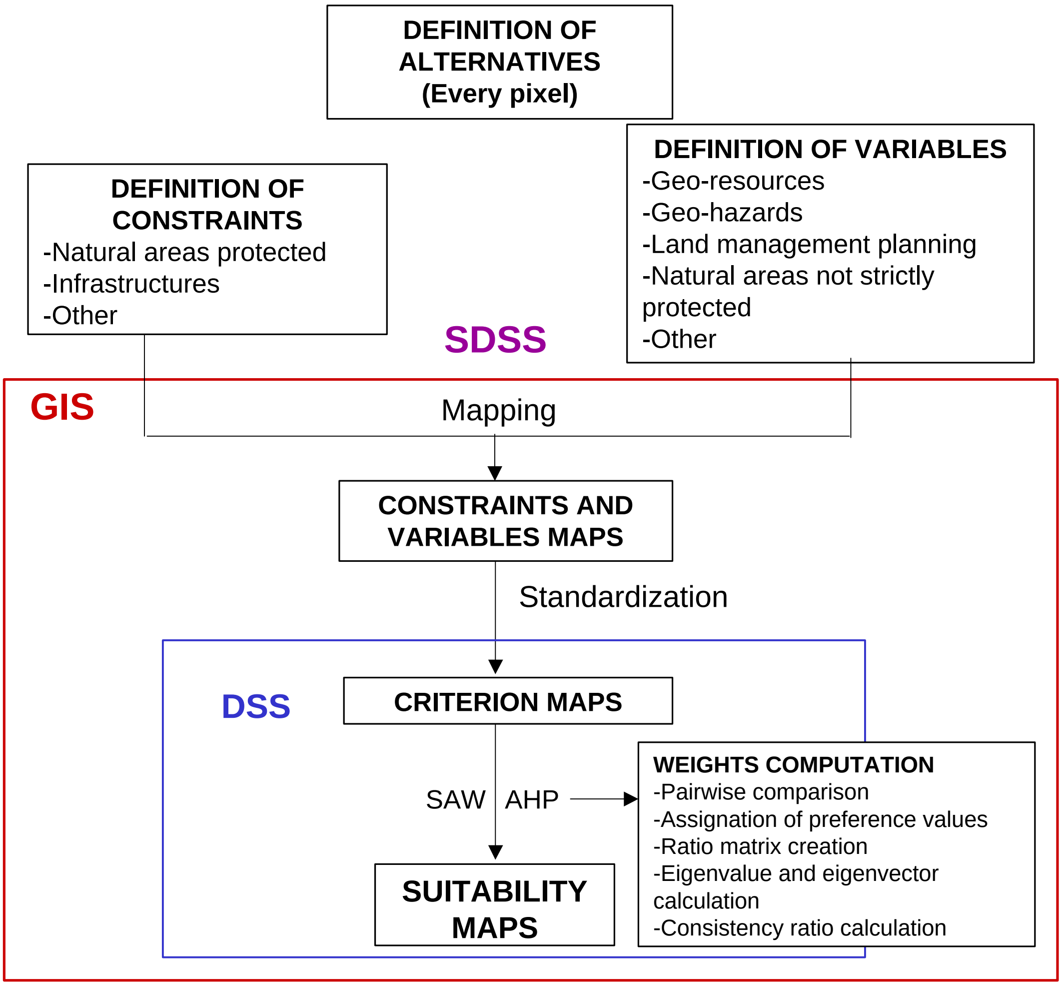


Figure 57: Scheme for the site search analysis. Source: Lamelas *et al*, 2006c.

As mentioned in chapter 2.3.4., in the Analytical Hierarchy Process, all identified criteria are compared against each other in order to create a ratio matrix. Thus, numerical values expressing the preference of one criteria against another should be assigned. Saaty (1977) suggested a scale for comparison consisting of values ranging from 1 to 9; value 1 being equal importance and value 9, extreme prevalence (Table 50).

Table 50: Scale for comparisons (slightly modified after Saaty and Vargas, 1991).

Importance value	Description
1	Equal importance
3	Moderate importance
5	Strong or essential importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values
Reciprocals	Values for inverse comparison

Afterwards, the assigned values are synthesized to determine a ranking of the criteria in terms of numerical values which are equivalent to the weights of the factors. Therefore, the eigenvalues and eigenvectors of the square preference matrix are calculated (Marinoni, 2004). According to Saaty and Vargas (1991), it is enough to calculate only the eigenvector resulting from the largest eigenvalue since this one contains sufficient information to determine the relative importance of the criteria.

Although the preference values are usually not arbitrarily assigned, the preference values selected by decision makers may be inconsistent and lead to perturbations in the eigenvector calculations. For this reason, Saaty (1977) additionally provided a single numerical index to check for consistency of the pairwise comparison matrix. The consistency ratio CR is the ratio of the consistency index CI to an average consistency index RI, thus

$$CR = CI/RI \qquad (6)$$

The resulting average consistency index RI was calculated by Saaty (1977) as the average consistency of square matrices of various orders n which was filled with random entries. According to Saaty (1977), matrices with an order greater than 8 have a RI order of about 1.45. The consistency index CI can be directly calculated from the preference matrix with

$$CI = (\lambda_{max} - n) / n - 1 \qquad (7)$$

where λ_{max} is the greatest eigenvalue of preference matrix and n the order of matrix. It is recommended that the consistency ratio presents values below 0.1.

The Analytical Hierarchy Process approach is of particular importance for problems involving a large number of alternatives represented by means of the raster data model, when it is impossible to perform a pairwise comparison of the alternatives (Eastman et al., 1993).

6.1.1. Sand and gravel extractions.

6.1.1.1. Definition of constraints

Constraints represent the areas under extraction restrictions. These restrictions are generally represented by the presence of other uses, the protection of natural areas, the inexistence of the resource due to previous exploitation or the different land-use planning present in the study area. In the case of sand and gravel extractions, these restrictions are:

- Infrastructures:

    i. Imperial Canal and other canals: information extracted for the topographic maps, scale 1:25,000, from the National Geographical Institute (IGN), imported to ArcGIS and updated (Map 4).

    ii. Roads: infrastructure and area of protection as defined by the Spanish Roads Law (Ley 25/1988, de 29 de Julio, de Carreteras). Highways are 10 m wide, plus 8 m of public domain and 25 m of protection (buffer 45 m from highway). While freeways are 20 m wide and have a public domain of 25 m and an area of protection of 50 m (buffer 100 m). Source of information: topographic maps (Map 4).

    iii. Train rails: infrastructure and area of protection according to the Spanish Railway Sector Law (Ley 39/2003, de 17 de Noviembre, del Sector Ferroviario). Rails are 10 m wide and have also 8 m of public domain and an area of protection of 50 m (buffer 70 m). Source of information: topographic maps (Map 4).

- Urban areas: information also taken from the topographic maps and in the case of great urban nucleus updating the area by using air photograph analysis (Map 4).

- Industrial areas: the source is a database of industrial areas from the Aragon Institute of Public Works (IAF, *Instituto Aragonés de Fomento*). This information may be downloaded from the internet (**http://www.iaf.es**). They offer analog plans that have been scanned and, sometimes, plans in CAD format. These plans required digitalization with the help of air photographs and, in the case of plans in CAD format, had to be imported to ArcGIS (Map 48).

- Natural protected areas: the Nature Reserve of *Los Galachos de La Alfranca, Pastriz, La Cartuja y El Burgo* is the only real natural protected area (Map 12).

- Cattle tracks: tracks traditionally used by the seasonal migration of livestock which are protected (Map 48).

- Areas already extracted: the information about old and present-day extractions was obtained from the Zaragoza Council which developed, in 2001, a study about the mining industry in the municipality (Manso et al., 2001). They also developed a Geographical Information System with information and cartography of extraction sites. This information required completion with information of the other municipalities within the study area, and with information from the Department of Mines in the Provincial Industrial Service from the Aragon Government. The information concerning the location of extractions appeared in analog plans that had to be located in air photographs and digitalized. Some extractions had geographical coordinates that required transformation to UTM and were imported to the Geographical Information System (Map 48). Two types of extractions can be observed. First, proper extraction sites of reduced dimensions, where the extraction activity is limited to the actual site. Second, *Concesiones de Explotación*, greater areas in which exploitation is permitted over a long period of time and different extraction sites may be developed.

- Land management planning from Zaragoza city (PGOUZ): according to this planning, extraction is not feasible in urban soils (SU), urban development soils (SUZ), since extraction of the material before construction is not economically viable, since the terrain must be filled again, and finally, areas without urban development (SNU) described in chapter 4.2.8., with the exception of the SNU EP (S). The cartography of classification of the soils according to the PGOUZ was supported by the Zaragoza Council (Map 14).

- PORN Ebro: according to the natural resources planning of the thickets and oxbows of the Ebro River, the areas not permitted for extraction purposes are zone 0A, 0B and 1 (see Map 12 and chapter 4.2.5. for description).

6.1.1.2. Definition of variables

A variety of social, economic and environmental attributes or variables are taken into consideration. These variables should play an important role in the decision process for the location of new sand and gravel extraction sites. These are:

- Distance to roads: the Environmental Impact Assessment Law (EIA) states that extraction sites should not be at less than 2 km distance from roads.

- Distance to nuclei with population over 1000 inhabitants: extraction sites should not be at less than 2 km distance, according also to Impact Assessment Law.

- Distance to existing extraction sites: no less than 5 km distance from present-day extractions, according to Impact Assessment Law.

- Distance to other natural protected areas: these are the natural areas included in the Natura network 2000 as SPAs, SACs, habitats which are not strictly restricted, but require environmental impact assessment prior to their utilization. It also incudes other areas which were mentioned in chapter 4.2 as sites of geological interest, wetlands, areas of the PORN with no strict restrictions, etc. Besides, it includes the Hydraulic Public Domain.

- Groundwater vulnerability: the model developed within Gocad was introduced in the process due to its higher quality and adaptation to reality. This factor is considered, since sand and gravel exploitation implies the reduction of the aquifer protection cover. Thus, more groundwater vulnerable areas should be protected from being exploited, because this will probably lead to higher contamination.

- Groundwater level: it is forbidden to exploit sites where the aquifer reaches surface. Also, areas with deeper water table are better, since the capacity of the resource can be higher. The model developed for doline susceptibility and groundwater vulnerability has been applied.

- Irrigation capability of the soils: the second approach of irrigation capability was used because it is highly recommended to preserve all resources in the study area. The area covered by soils with good irrigation capability is low. In fact, almost all soils with good irrigation capability are already used for this purpose. In this case, the lower the irrigation capability, the higher the extraction suitability.

- Geo-resource location: the sand and gravel thickness model is used, because a thick resource also means a lower impact on the environment, due to the fact that the exploited surface area can be reduced.

- Overburden: according to the model developed in chapter 4. This factor is introduced because when the overburden is very thick the exploitation becomes economically unfeasible.

6.1.1.3. Transformation into criteria

These variables should be standardized befor they can be transformed into criteria. The standardization method used may be inserted in the subjective scales approach, according to Malczewiski (2004), since the variables are classified in subjective ranges. These ranges are selected following, in some cases, indications by law or, in other cases, the classes already determined for the performed models. This methodology can be also inserted in the value function approach, when in some cases a central value determining good or bad suitability is selected. Then, the values are classified into 6 categories: from 1 to 3 bad suitability values; and from 4 to 6 positive values.

Six categories were selected considering the adaptation of these classes to the variables to be introduced. This number of categories was selected because the maximum number of classes in the models to be introduced in the land-use suitability analysis was five, and it is usually necessary to save another category for the areas outside some models, *i.e.* the groundwater vulnerability, water table level and doline susceptibility models, which do not cover the whole study area.

In this case, the application of the suitability analysis in the Geographical Information System, requires a value outside the model area. The highest value of suitability (value 6) was assigned outside the model areas, because it was assumed that the groundwater vulnerability and the doline susceptibility is lower in these sectors.

In the case of the water table and groundwater vulnerability, this is relatively obvious, since the Quaternary Aquifer is not present outside the model area. Besides, although the Tertiary Aquifer is supposed to discharge on the Quaternary Aquifer, the travel time of a possible contaminant to arrive at the Quaternary Aquifer would be higher outside the model area than inside it, where the Quaternary Aquifer is present. Thus, groundwater vulnerability would be lower outside the Quaternary Aquifer area than inside it.

With respect to doline development, the authors of the existing literature agree that the most hazardous area in this sector is the covered karst area, where the Quaternary sediments lie directly on the Tertiary sediments. Thus, it is possible to assume that outside the model area, where the Tertiary sediments are at the surface, the dolines susceptibility is lower.

The same problem may be observed in the resource thickness model. In the area outside the model, there is generally no resource, so value 1 (worst suitability) has been assigned to these areas, with the exception of the higher terraces of the Ebro downstream of Zaragoza and the *Huerva* Valley. According to the literature, these terraces have thicknesses between 15 and 25 m (I.T.G.E., 1998c; I.T.G.E., 1998d; Manso *et al*., 2001). Thus, the value 15 m has been given to these areas as minimum thickness, and value 6 in the classification of criteria.

In the overburden mapping, the area outside the model is given the value 1 (worst suitability), due to the lack of resource. Finally, the categories used are (Map 49):

- Distance to roads; taking into account the Environmental Impact Assessment Law, it was decided to give values from 1 to 3 to distances between 0 and 2 km, and values from 3 to 6 to distances greater than 2 km:
    i. 0-500 m = 1.
    ii. 500-1000 m = 2.
    iii. 1000-2000 m = 3.
    iv. 2000-3000 m = 4.
    v. 3000-4000 m = 5.
    vi. > 4000 m = 6.

- Distance to urban nuclei over 1000 inhabitants; same ranges as distance to roads.

- Distance to present-day and old extraction sites; taking into account the Environmental Impact Assessment Law, it was decided to give values from 1 to 3 to distances between 0 and 5 km, and values from 3 to 6 to distances greater than 5 km:
    i. 0-1000 m = 1.
    ii. 1000-3000 m = 2.
    iii. 3000-5000 m = 3.
    iv. 5000-7000 m = 4.
    v. 7000-10000 m = 5.
    vi. > 10000 m = 6.

- Groundwater protection; ranges divided according to total score (see chapter 5.3.):
    i. 0 – 500 = 1.
    ii. 500-1000 = 2.
    iii. 1000-2000 = 3.
    iv. 2000-4000 = 4.
    v. > 4000 = 5
    vi. Outside the model = 6

- Irrigation capability of the soil; ranges divided according to the irrigation capability model (see chapter 4.3.7.):
    i. Calcaric Fluvisols with irrigation capability S2c = 1.
    ii. Petric Calcisols of irrigation capability S2drc = 2.
    iii. Calcaric Cambisols of irrigation capability S2rcg = 3
    iv. Haplic Gypsisols of irrigation capability S3g = 4
    v. Calcaric Regosols of irrigation capability S3dg = 5.
    vi. Haplic Solonchaks of irrigation capability Nl = 6.

- Distance to natural areas; these areas are not strictly protected by law and only require environmental impact assessment in case of use. In addition, future extraction should be more than 2 km from these areas and it is our opinion that they should be protected. Accordingly, value 1 (worst suitability) is given inside the natural areas and values 2 to 3 to distances lower than 1 km:
    i. Inside the natural area = 1.
    ii. 0-500 m = 2.
    iii. 500-1000 m = 3.
    iv. 1000-2000 m = 4.
    v. 2000-4000 = 5.
    vi. > 4000 m = 6.

- Water table depth; extraction should be stopped when it reaches water table level. In addition, extraction is not economically viable in thin occurrences of raw material. Thus after some talks with experts in the Zaragoza council, Aragon Government and Ebro River Authority, it was decided to give value 1 (worst suitability) to water table depth values under 7 m, implying less than 7 m thickness of raw material. Greater water table depths get values from 4 and 5 until the 15 m depth, which get the highest suitability values:
    i. 0-7 m = 1.
    ii. 7-10 m = 4.
    iii. 10-15 m = 5.
    iv. > 15 m = 6.
    v. Outside model = 6

- Resource thickness; this variable is classified following economical and environmental criteria as thicker resources imply less environmental impact because of the reduction in surface extension of the extraction, and also more economical viability. The ranges were also selected after some talks with the above mentioned experts and the diference with the ranges in water table depth are due to the fact that in *i.e.* 7 meter of water table depth only part of the profile correspond to gravel and sand:

i. 0-5 m = 1.
ii. 5-7 m = 4.
iii. 7-10 m = 5.
iv. > 10 and Terraces outside model = 6.
v. Outside the model = 1.

- Overburden thickness; this variable was also classified following the suggestions of the experts. It was decided to give the worst suitability value to overburden thickness greater than 5 m (values 2 and 1), medium-good suitability values to thickness lower than 5 m (value 4) and the best suitability values to thickness lower than 3 (value 6):

i. 0-3 m = 6.
ii. 3-5 m = 4.
iii. 5-10 m = 2.
iv. > 10 m = 1.
v. Outside model = 1

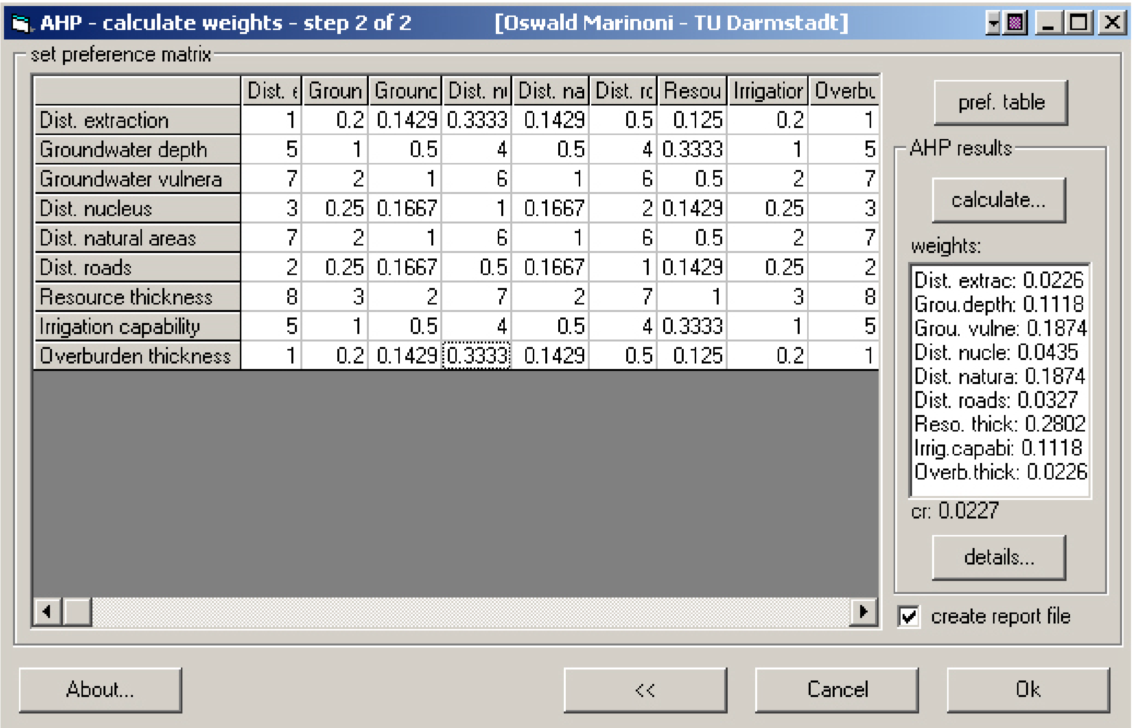
6.1.1.4. Assigning decision weights and mapping

As mentiones in chapter 6.1, weights for criteria are assigned in the Analytical Hierarchy Process with the help of the pairwise comparison matrix, which is a measure to express the relative preference among the factors. Therefore, numerical values expressing a judgement of the relative importance (or preference) of one factor against another have to be assigned to each of them. Saaty (1977) and Saaty and Vargas (1991) suggested a scale for comparison consisting of values ranging from 1 to 9 which describe the intensity of importance (Table 50).

Figure 58 shows this matrix within the windows of the tool developed for the Geographical Information System environment by Oswald Marinoni. These windows also show the weights assigned to every criterion when the “calculate” button is activated. In this case, the consistency ratio (CR), which measures the consistency of the values assigned in the criteria matrix, presents a value of 0.0227, which is bellow the recommended value 0.1.

The criteria weights have the strongest impact on the results. Hence the determination of the preference values is often subject to debate among the interest groups involved (Hoppe *et al*., 2006a). In this case, weights have been assigned by ourselves after having some conversations with different stakeholders belonging to Zaragoza Council, Aragon Government and Ebro River Authority. The highest weight has been assigned to the location of the resource (value 0.2802), as, in this case, this factor extremely determines the possibility to extract (Figure 58). Obviously, when there is no resource, it is impossible to exploit it.

The ground water vulnerability (0.1874), natural protected areas (0.1874), irrigation capability of the soils (0.1118) and groundwater depth factors (0.1118) have also very high values, because it is our opinion that the main objective of a sustainable development is to protect geo-resources. It is followed by the distance to nuclei (0.0435), roads (0.0327) and extractions (0.0226), because it is our opinion that it is less important to impact human beings visually, than to impact environment. Finally, the lowest value has been assigned to overburden thickness (0.0226) as, in the area, the terraces below pediments of even 15 m thickness are being extracted.



	Dist. e	Groun	Grounc	Dist. nı	Dist. na	Dist. rc	Resou	Irrigatior	Overbu
Dist. extraction	1	0.2	0.1429	0.3333	0.1429	0.5	0.125	0.2	1
Groundwater depth	5	1	0.5	4	0.5	4	0.3333	1	5
Groundwater vulnera	7	2	1	6	1	6	0.5	2	7
Dist. nucleus	3	0.25	0.1667	1	0.1667	2	0.1429	0.25	3
Dist. natural areas	7	2	1	6	1	6	0.5	2	7
Dist. roads	2	0.25	0.1667	0.5	0.1667	1	0.1429	0.25	2
Resource thickness	8	3	2	7	2	7	1	3	8
Irrigation capability	5	1	0.5	4	0.5	4	0.3333	1	5
Overburden thickness	1	0.2	0.1429	0.3333	0.1429	0.5	0.125	0.2	1

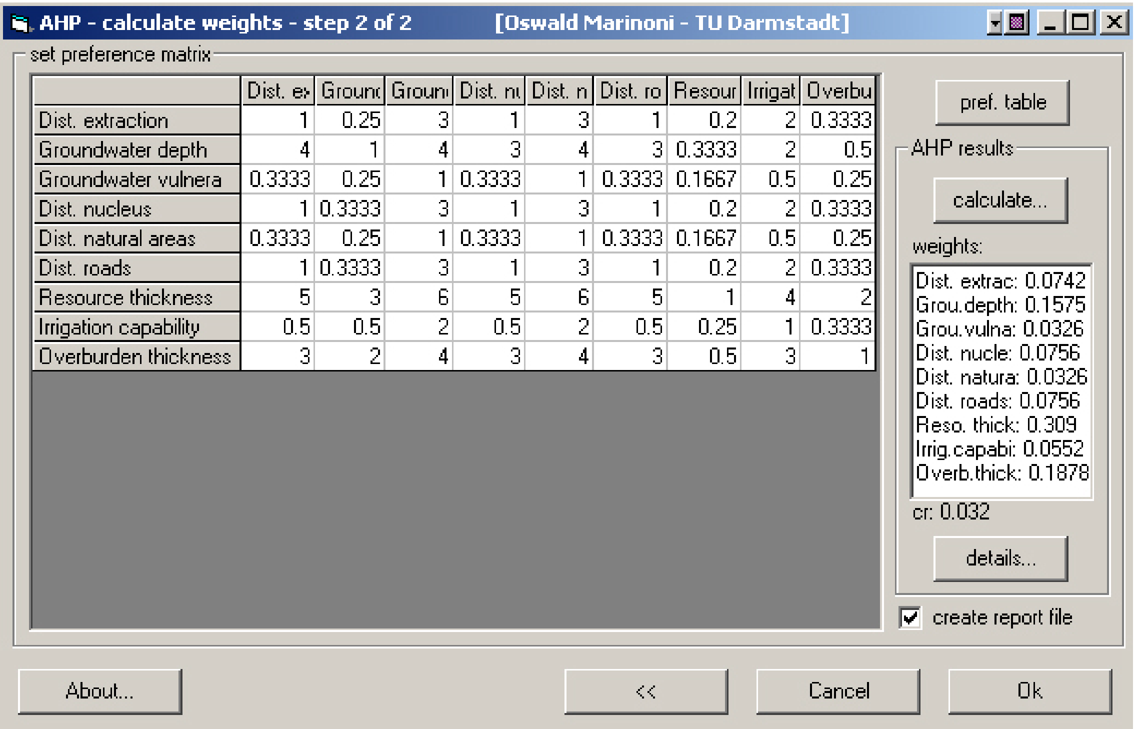
Figure 58: Pairwise comparison matrix, criteria weights and consistency ratio for extraction location.

At a last step, all the classified raster files (criteria) are multiplied by its corresponding weight, and summed up following a *Weighted Linear Combination* (*WLC*) approach, also known as *Simple Additive Weighting (SAW)* method (see chapter 6.1.).

Map 50 shows the suitability map for extraction location. The transparent grey sections indicate the areas where extraction is not possible due to the constraints. Although the suitability analysis sometimes presents good values, as may be observed in the maps, the transparency of constraints shows that these areas cannot be exploited due to any restriction. The areas more suitable to sand and gravel extraction (green colours) are located in the high terraces, and in those terraces covered by pediments where the thickness of resource is relatively high. Besides, these areas are far from valuable natural areas, outside the areas most vulnerable to groundwater contamination, and beneath soils with poor irrigation capability. In fact, these are the areas that are currently exploited.

In addition to areas without resources, the less suitable areas (red and yellow colours) are located in the low terraces were groundwater vulnerability is higher and water table level is nearer to the surface. This is the case in the surroundings of *La Alfranca* where very thick deposits of sand and gravel are found. However these sites also have a high groundwater vulnerability and are close to natural valuable areas.

As explained above, criteria weights have the strongest impact on the results. Thus, in order to obtain an idea of the degree by which these weights affect the final result, a second approach was carried out awarding higher weights to economical aspects, *i.e.* overburden thickness, than to the environmental criteria. Besides, the visual component of the landscape was given a greater value and, as a consequence, distance to roads and urban nuclei over 1000 inhabitants obtain higher weight values (Figure 59).



	Dist. ex	Ground	Groun	Dist. nu	Dist. n	Dist. ro	Resour	Irrigat	Overbu
Dist. extraction	1	0.25	3	1	3	1	0.2	2	0.3333
Groundwater depth	4	1	4	3	4	3	0.3333	2	0.5
Groundwater vulnera	0.3333	0.25	1	0.3333	1	0.3333	0.1667	0.5	0.25
Dist. nucleus	1	0.3333	3	1	3	1	0.2	2	0.3333
Dist. natural areas	0.3333	0.25	1	0.3333	1	0.3333	0.1667	0.5	0.25
Dist. roads	1	0.3333	3	1	3	1	0.2	2	0.3333
Resource thickness	5	3	6	5	6	5	1	4	2
Irrigation capability	0.5	0.5	2	0.5	2	0.5	0.25	1	0.3333
Overburden thickness	3	2	4	3	4	3	0.5	3	1

Figure 59: Pairwise comparison matrix, criterion weights and consistency ratio for the second approach in extraction location.

Map 51 shows the slightly different results of this last approach. The extension of suitable areas for sand and gravel extraction has been considerably improved, especially in the low terraces of the rivers, because the groundwater vulnerability factor loses importance. This is the case of the surroundings of *La Alfranca* which presented low suitability values under sustainability aspects, mainly due to the low groundwater protection. However, in the case of sand and gravel extraction, the results do not vary extremely in comparison to other models, *i.e.* irrigation location.

6.1.1.5. Potential conflicts between stakeholders

A good way of recognizing potential stakeholders´ conflicts is to sum up the results of the suitability analysis from different stakeholders. Map 52 shows the addition of the two sand and gravel extraction suitability analysis performed in the previous chapters. The areas with additive suitability values below 8 are presented in red colour. These are areas that present low suitability values below 4, at least for one of the stakeholders involved in the decision process. Thus, these areas should be avoided, in order to evade stakeholders´ conflict. Areas of good suitability (values between 8 and 10) with minor conflicts between stakeholders are presented in yellow and the green colour (values between 10 and 12) indicates areas of excellent suitability without conflicts.

6.1.2. Irrigated areas

6.1.2.1. Definition of constraints

The constraints are sometimes similar when considering the location of new irrigated areas: presence of other uses and infrastructures and protection of natural areas (see chapter 6.1.1.1.). The different land-use plannings present different constraints with respect to irrigation use. Besides, areas already irrigated are added to the constraints. The restrictions are:

- Infrastructures:
    - i. Imperial Canal and other canals.
    - ii. Roads
    - iii. Train rails.
- Urban areas.
- Industrial areas.
- Natural protected areas: the Natural Reserve of *Los Galachos de La Alfranca, Pastriz, La Cartuja y El Burgo*.
- Cattle tracks.
- Areas already irrigated: information based on the cartography of irrigated areas in 2000, available online on the CHE web page (Map 34).
- Land management planning from Zaragoza city (PGOUZ): according to this planning, the areas where irrigation is not permitted are the urban soils (SU), the urban development soils (SUZ), and, finally, areas of no urban development (SNU) described in chapter 4.2.8., with the

exception of the SNU EP (S), SNU EP (R), SNU EP (HH), SNU EN (CC).

- PORN Ebro: according to the natural resources planning of the thickets and oxbows of the Ebro River, the areas not allowed for new irrigation purposes are zone 0A, 0B and 1.

6.1.2.2. Definition of variables

The decision variables change slightly in the case of the irrigation suitability analysis. However, there are some variables that remain the same, such as groundwater vulnerability, the protected natural areas or the irrigation capability of the soil (see chapter 6.1.1.2.). These variables are:

- Other protected natural areas: this variable includes the same areas outlined in the extraction location, using, in this case, only the exact location and not the distance.

- Groundwater vulnerability: in this case, this factor is even more important, since irrigation is the main source of water recharge of the aquifer. The model introduced in the suitability analysis is the groundwater under natural conditions, since it is important to differentiate more or less vulnerable areas previously irrigated in order to identify the more or less suitable areas to be irrigated (see chapter 5.3.).

- Irrigation capability of the soils: in this case, the higher the quality, the higher the suitability of the terrain to irrigation use.

- Doline susceptibility: the model developed with the logistic regression was introduced here because the input of water by irrigation may considerably increase doline development. Thus, more susceptible areas should be avoided.

- Change in erosion hazard when irrigating: the approach developed in chapter 5.1.8. was used.

- Slope percentage: different ranges of slope percentage improve or reduce the suitability of the terrain to be irrigated. For instance, slopes over 15% are almost economically unviable, considering the type of crop typically grown in the study area and its market price.

- Elevation: this factor represents the area with elevation below a certain limit, where irrigation is economically viable. In the study area, according to INARSA (1992), it is viable to technologically raise the water between 50 and 100 m above any possible source of water. The Imperial Canal follows the 250 m contour line; this allows irrigation below 350 m. Besides, a possible future canal to be constructed on the right bank of the Ebro River, parallel to the Imperial canal, according to the project, would follow the 390 m contour. This would allow irrigation below 490 m.

6.1.2.3. Transformation into criteria

The transformation method used for irrigation location is similar to the one used for sand and gravel extraction. Only, the groundwater vulnerability and doline susceptibility models present areas without information; these are also considered more suitable than the areas inside the model for irrigation location and obtain, as a consequence, value 6. Finally, the categories used are (Map 53):

- Groundwater vulnerability; ranges divided according to total score (see chapter 5.3.):
    i. 0 – 500 = 1.
    ii. 500-1000 = 2.
    iii. 1000-2000 = 3.
    iv. 2000-4000 = 4.
    v. > 4000 = 5
    vi. Outside the model = 6

- Irrigation capability of the soil; ranges divided according to the irrigation capability model (see chapter 4.3.7.):
    i. Calcaric Fluvisols with irrigation capability S2c = 6.
    ii. Petric Calcisols of irrigation capability S2drc = 5.
    iii. Calcaric Cambisols of irrigation capability S2rcg = 4
    iv. Haplic Gypsisols of irrigation capability S3g = 3
    v. Calcaric Regosols of irrigation capability S3dg = 2.
    vi. Haplic Solonchaks of irrigation capability Nl = 1.

- Natural areas location; in this case the Environmental Impact Assessment Law only requires impact assessment in case of irrigation projects inside the natural areas. Thus, value 1 (worst suitability is given to areas inside the perimeter of a natural space and best suitability values (value 6) to areas outside it:
    i. Inside the natural area = 1.
    ii. Outside natural areas = 6.

- Doline susceptibility; ranges have been assigned according to the doline susceptibility model. As mentioned in chapter 5.2.4., for the division between probability of dolines or not, the percentage of dolines in the sample (in our case 6%) should be selected. Thus, the areas with probability values greater than 0.06 were classified with the worst suitability value (value 1) and the areas with lower probability values (< 0.02) were given the second best suitability value (value 5), as value 6 was saved for the area outside the model:

i. > 0.06 = 1.
ii. 0.04-0.06 = 2.
iii. 0.02-0.04 = 3.
iv. < 0.02 = 5.
v. Outside the model = 6

- Change in erosion hazard; classified according to the decrese in erosion susceptibility when irrigated model (see chapter 5.1.8):

  i. 0 = 1.
  ii. 9 = 4.
  iii. 13 = 6.

- Slope percentage; ranges have been assigned according to INARSA (1992), which suggested that slopes greater than 15% are not suitable to be irrigated and classified the suitability values in three ranges (< 5 %, 5 - 10 % and 10 - 15 %):

  i. < 5 % = 6.
  ii. 5-10 % = 5.
  iii. 10-15 % = 4.
  iv. > 15 % = 1.

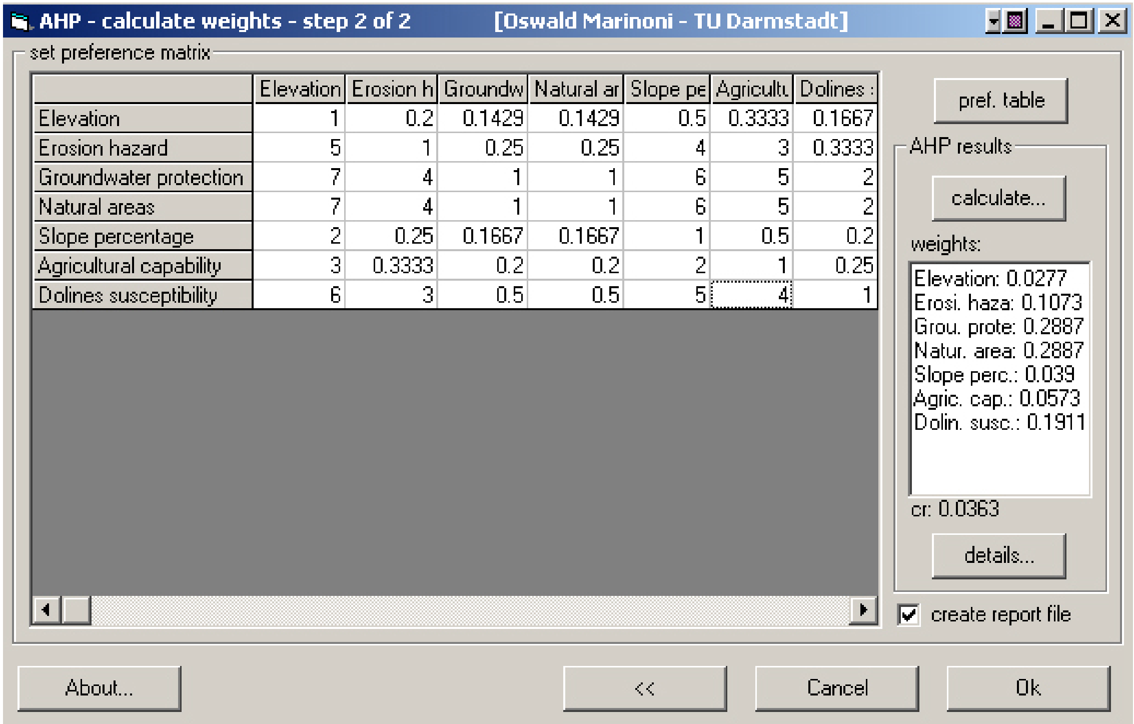
- Elevation above sea level; ranges have been assigned according to the study from INARSA (1992) (see chapter 6.1.2.2.). The worst suitability values have been given to areas located 100 m above the posible future canal which would follow the 390 m.a.s.l. contour. The highest suitabilty values have been given to areas below 350 m.a.s.l. which can be at present irrigated by the Imperial Canal:

  i. < 350 m = 6.
  ii. 350-390 m = 5.
  iii. 390-440 m = 4.
  iv. 440-490 m = 3.
  v. > 490 m = 1.

6.1.2.4. Assigning decision weights and mapping

Figure 60 shows the comparison matrix, the decision weights assigned to each criterium and the consistency ratio (0.0363), which is lower than the recommended limit of 0.1. The magnitude of the assigned criteria weights are also based on conversations with different stakeholders belonging to the Department of Irrigation and Soils of the Agricultural Research Center (CITA, *Centro de Investigación y Tecnología Agroalimentaria*), the Aula Dei Scientific Research National Center (CSIC, *Centro Superior de Investigaciones Cientificas*) and the Ebro River Authority.

The highest weights were again assigned to groundwater vulnerability (0.2887) and protected natural areas factor (0.2887), since irrigation can be a source of aquifer contamination, because this aquifer is mostly recharged by irrigation. The doline susceptibility factor (0.1911) follows in magnitude, since irrigation is considered one of the main factors affecting dolines development. Slope (0.039) and elevation (0.0277) factors receive the lowest values, since these can be solved by the application of new technology.



	Elevation	Erosion h	Groundw	Natural ar	Slope pe	Agricultu	Dolines :
Elevation	1	0.2	0.1429	0.1429	0.5	0.3333	0.1667
Erosion hazard	5	1	0.25	0.25	4	3	0.3333
Groundwater protection	7	4	1	1	6	5	2
Natural areas	7	4	1	1	6	5	2
Slope percentage	2	0.25	0.1667	0.1667	1	0.5	0.2
Agricultural capability	3	0.3333	0.2	0.2	2	1	0.25
Dolines susceptibility	6	3	0.5	0.5	5	4	1

Figure 60: Pairwise comparison matrix, criteria weights and consistency ratio for irrigation location.

Map 54 shows the final irrigation suitability map under the concept of sustainable development. The more suitable areas are located in a small sector in the south-west of the study area, in a zone where the pediments produce a smooth slope to the terrain, and with low values of groundwater vulnerability and doline susceptibility. The lowest values of suitability (red and orange values) correspond to the thickets in the vicinity of the river and protected steppes in the south-east of the area, which also have a high slope percentage.

A sensitivity analysis was also performed in the case of irrigation. This involved changing the criteria weights, following a more traditional economically oriented way of thinking. In the past this gave more importance to the physical characteristics of the soils and the terrain (slope and elevation). Figure 61 shows the pairwise comparison matrix, criteria weights and consistency ratio. Thus, the highest values are assigned to irrigation capability of the soils (0.3601), slope percentage (0.2297) and elevation above sea level (0.1655). The lowest values were given to erosion hazard (0.0309), doline susceptibility (0.0444) and natural areas protection (0.0669). Map 55 shows the results of the irrigation suitability analysis. According to these weights, the most suitable areas for irrigation are the traditionally irrigated areas, the low terraces and flood plains that have soils with better characteristics for irrigation, a low slope percentage and low elevation, which facilitate irrigation.

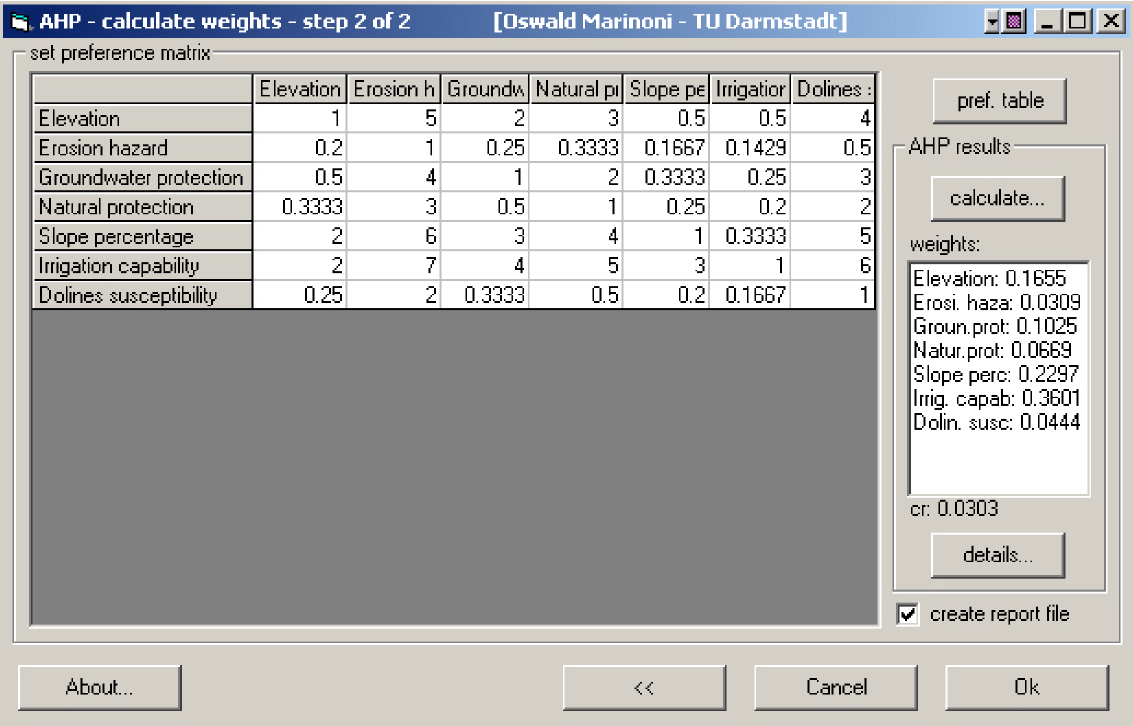


Figure 61: Pairwise comparison matrix, criteria weights and consistency ratio for irrigation location under economic aspects.

6.1.2.5. Potential conflicts between stakeholders

Map 56 shows the results of the potential conflict between stakeholders for irrigation suitability. The areas of low conflict are mainly located in the pediments in the south-west of Zaragoza and the high terraces of the *Huerva* Valley at the south of the area of study.

6.1.3. Industrial settlements

6.1.3.1. Definition of constraints

The constraints governing the location of new industrial areas are also very similar. The main difference is found among the industrial areas. Here, only the industrial areas without free space for new industries are included as constraints. The different land-use plannings also have different constraints with respect to industrial use. The restrictions are:

- Infrastructures:
    i. Imperial Canal and other canals.
    ii. Roads.
    iii. Train rails.
- Urban areas.
- Industrial areas without free space.
- Natural protected areas: the Natural Reserve of *Los Galachos de La Alfranca, Pastriz, La Cartuja y El Burgo*.
- Cattle tracks.
- Land management planning from Zaragoza city (PGOUZ): according to this planning the areas that cannot be used for location of industries are areas of no urban development (SNU) described in chapter 4.2.8.
- PORN Ebro: according to the natural resources planning of the thickets and oxbows of the Ebro River, the areas not allowed for industrial location almost cover the whole PORN area: zone 0, 1 and 2.

6.1.3.2. Definition of variables

The decision variables also change for the industrial suitability analysis. These variables are:

- Other protected natural areas: this variable includes the same areas as in the extraction and irrigation location. In this case only the exact location is essential and not the distance to these areas (see chapter 6.1.1.2. and 6.1.2.2.).
- Groundwater vulnerability: in this case, this factor is also of great importance, since industry, as well as irrigation, is one of the main sources of aquifer contamination. The model introduced in the suitability

analysis is the groundwater under present-day conditions, including irrigation (see chapter 5.3.).

- General agricultural capability of the soils: this resource should be also protected for agricultural use (see chapter 4.3.).

- Doline susceptibility: the more susceptible areas should be avoided for construction in order to avoid risk.

- Flood risk: it is also necessary to avoid the most hazardous areas. The flooding hazard mapping developed by Ollero (1996) was digitised and introduced in the land-use suitability analysis and shows the different periods of return of flood events.

- Slope percentage: different ranges of slope percentage improve or reduce the suitability of the terrain for construction.

- Geotechnical characteristics of the soils: according to the PGOUZ, there are different geomorphological units with better or worse geotechnical characteristics. This classification has been applied to the geomorphological units derived from the Geological map, scale 1:50,000, from ITGE.

6.1.3.3. Transformation into criteria

In the case of industrial suitability analysis, the categories used for transforming variables into criteria are (Map 57):

- Groundwater vulnerability; ranges divided according to total score (see chapter 5.3.).
    - i. 0 – 500 = 1.
    - ii. 500-1000 = 2.
    - iii. 1000-2000 = 3.
    - iv. 2000-4000 = 4.
    - v. > 4000 = 5
    - vi. Outside the model = 6
- Natural areas location; see explanation in section 6.1.2.3.:
    - i. Inside the natural area = 1.
    - ii. Outside natural areas = 6.
- Doline susceptibility; ranges were assigned according to the doline susceptibility model (see explanation in section 6.1.2.3.):
    - i. > 0.06 = 1.
    - ii. 0.04-0.06 = 2.

iii. 0.02-0.04 = 3.
iv. < 0.02 = 5.
v. Outside the model = 6

- Flooding hazard; according to the division by Ollero (1996) in periods of return of floodings, values 1, 3, 5 were assigned to areas with 5, 50 and 500 year period of return and value 6 (best suitability) to areas outside the model:
  i. Period of return 5 years = 1.
  ii. Period of return 50 years = 3
  iii. Period of return 500 years = 5.
  iv. No data = 6.

- General agricultural capability of the soils; classified according to the general agricultural capability of the soils (see chapter 4.3.6.). In this case, the areas with no soils are given the worst suitability values, as these are usually already urbanized. Soils with the best agricultural capability are given value 3 (also bad suitability) and the soils with the lowest capability values are given the worst suitability values (from 4 to 6).
  i. No soils = 1.
  ii. S3b = 3 .
  iii. S3bl = 4.
  iv. S3blt = 5.
  v. Nl = 6.

- Slope percentage; these ranges were determined following talks with experts in the Zaragoza council. It was decided to specify a 10 % slope (giving this value between suitability values 3 and 4) as the threshhold value between good and bad suitability. In addition, the most suitable areas were considered to be flat or almost flat surfaces, therefore value 6 was given to areas with slope percentages below 2. Areas with slopes above 30 % are unsuitable for construction purposes. These areas were assigned value 1 (worst suitability):
  i. 0-2 % = 6.
  ii. 2-5 % = 5.
  iii. 5-10 % = 4.
  iv. 10-15 % = 3.
  v. 15-30 % = 2.
  vi. > 30 % = 1.

- Geotechnical characteristics of the soil; according to the Land Management Planning the terrain can be divided into three sectors in order to describe the geotechnical characteristics. Terrains with bad geotechnical characteristics are given the worst suitability values (value 1) and those described as medium and good geotechnical characteristics are assigned values 3 and 6 respectively:
    - i. Flood plain, river, slopes in Tertiary materials, endorheic areas, alluvial fans and flat bottom valleys = 1.
    - ii. Low terraces = 3.
    - iii. Pediments and high terraces = 6.

6.1.3.4. Assigning decision weights and mapping

Figure 62 shows the comparison matrix, the decision weights assigned to every criteria and the consistency ratio (0.0168), which is below the recommended limit of 0.1. The criteria weights were assigned with the help of stakeholders belonging to the Zaragoza Council and Ebro River Authority.

The highest weights were assigned to the groundwater vulnerability criteria (0.2888) and protected natural areas (0.2888) as it is our opinion that the main objective of a sustainable development is to protect the geo-resources. This is followed by the different hazards (doline susceptibility, 0.1736, and flooding hazard, 0.1131). These are considered less important, since these hazards may be avoided by employing new construction techniques. This is also the case of the two least important factors, slope (0.0251) and geotechnical characteristics of the soils (0.0427).

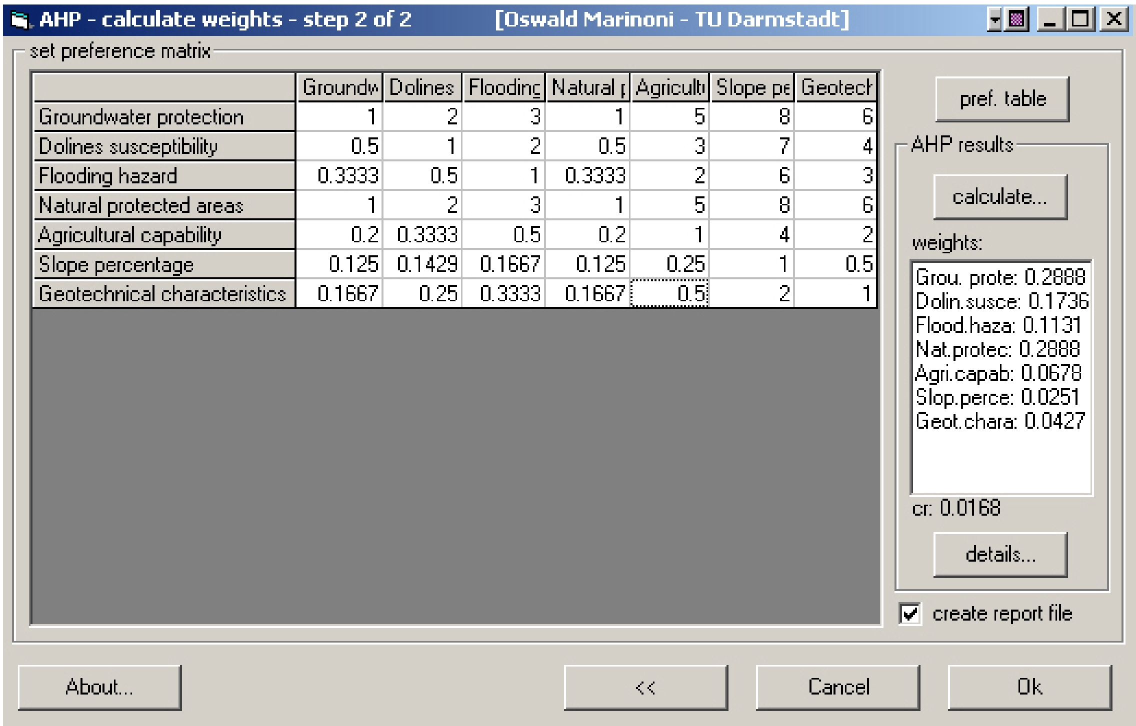


Figure 62: Pairwise comparison matrix, criteria weights and consistency ratio for industrial location.

Map 58 shows the final results of the land-use suitability analysis for the location of new industrial areas. The best location for new industries is on the pediments and Tertiary sediments outside the protected natural areas, where the groundwater vulnerability and flood risk is lower, although the geotechnical characteristics of the terrain are less favourable. The worst location is the floodplain with high groundwater vulnerability values and the protected natural areas around the river bed as well as other areas in the higher terraces which are more susceptible to doline development.

For industrial location, a sensitivity analysis was also performed by changing the criteria weights to more economically oriented thinking. Figure 63 shows the pairwise comparison matrix, criteria weights and consistency ratio (0.0479). The highest weights were assigned to doline susceptibility (0.3492) and flooding hazard (0.1774), which might cause the destruction of future industrial sites. In addition to this, slope (0.1892) and geotechnical characteristics of the soils (0.1378) are also assigned high values, due to the difficulty in the terrain, which increases the construction budget.

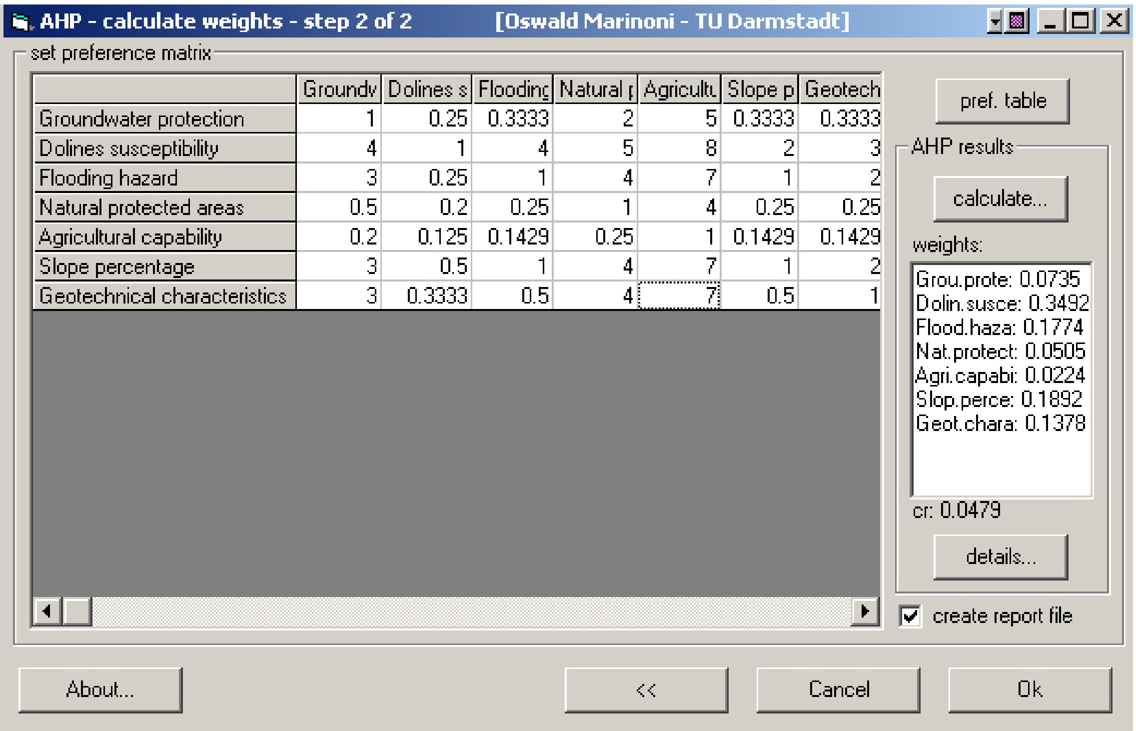


Figure 63: Pairwise comparison matrix, criteria weights and consistency ratio for industrial location under economic aspects.

Map 59 shows the results of the industrial suitability analysis under a more economic perspective. These results do not differ excessively from the previous results. Thus, the best locations for industry are the pediments and slopes in Tertiary sediments, and the worst location is the flood plain and low terraces, where sinkhole susceptibility shows higher values.

6.1.3.5. Potential conflicts between stakeholders

Map 60 shows the results of the potential conflicts analysis for the location of industrial areas.The lower conflicts are located in the pediments just to the south-west of Zaragoza city, where the Logistic Platform is currently under construction. Low conflict is also found in some sectors north and north-east of the structural platform *La Muela*, where some new industrial areas have been built recently. And finally, the south of *La Cartuja* village, where the Technologic Recycling Centre is being built.

6.1.4. Urban constructions

6.1.4.1. Definition of constraints

The new urban areas suitability analysis is almost the same as the industrial suitability, but with small differences. In the case of the constraints, the only difference is that all the industrial areas, with or without space, are restricted.

6.1.4.2. Definition of variables

The decision variables are also the same as in the industrial suitability analysis, with the exception of the groundwater vulnerability, which is not included, as it was considered that urban construction is not a major threat to this resource.

6.1.4.3. Transformation into criteria

According to the previous chapter, the categories used for transforming variables into criteria are similar to those used for industrial location (with the exception of groundwater protection, which is not included), and are described in chapter 6.1.3.3. and Map 57.

6.1.4.4. Assigning decision weights and mapping

Figure 64 shows the comparison matrix, the decision weights assigned to every criteria and the consistency ratio (0.0232), which is under the recommended limit of 0.1. The criteria weights were assigned with the help of stakeholders belonging to the Zaragoza Council and Ebro River Authority.

The highest weights were assigned to the protected natural areas (0.3893). These achieve a much greater degree of importance, since the other main resource present in the study area (groundwater) is not affected. This is followed by doline susceptibility (0.2495), which is also of greater importance, and flooding hazard (0.1775). The two least important factors are slope (0.0321) and geotechnical characteristics of the soils (0.0537). The justification is similar to that for industrial suitability.

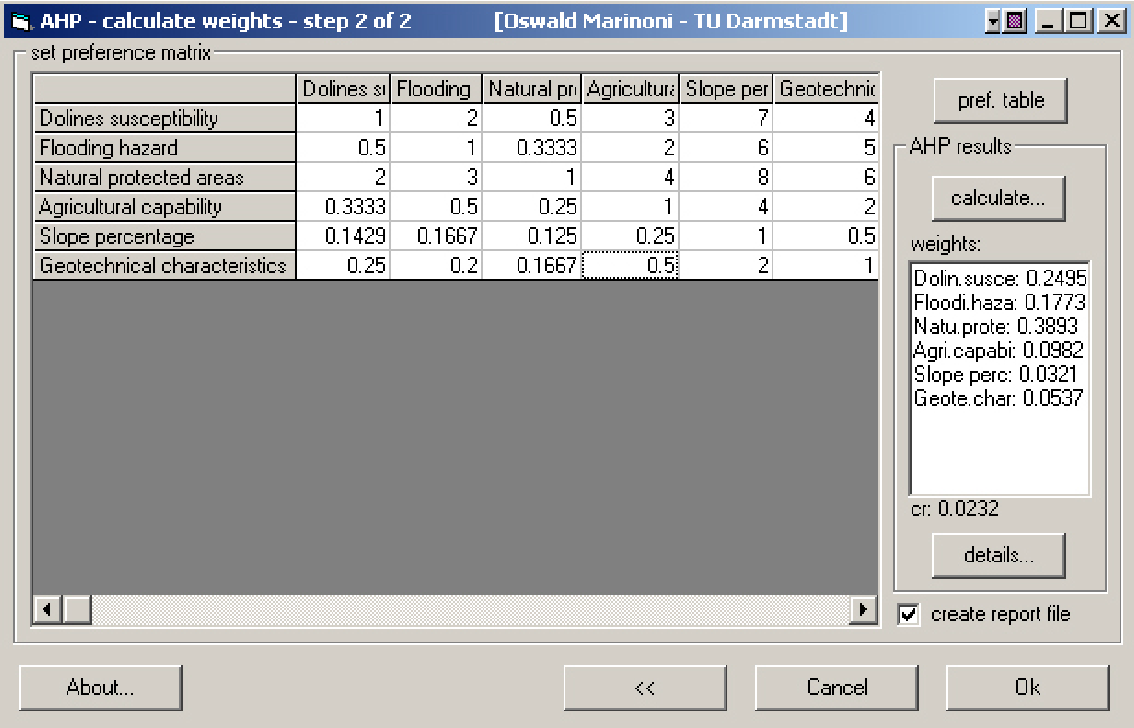


Figure 64: Pairwise comparison matrix, criteria weights and consistency ratio for urban location.

Map 61 shows the final results of the land-use suitability analysis for new urban area location. The best zones for a new location of urban areas are situated in the contact between terraces and pediments south and south-west of Zaragoza. Besides, some sectors along the *Huerva* and *Jalón* Valleys and north or north-east of the *La Muela* structural platform also achieve good suitability values. The least suitable areas are the steppes in Tertiary sediments and natural areas along the Ebro shores.

With respect to the sensitivity analysis, Figure 65 shows the values selected for the confusion matrix. In this case, following a more economical thinking, the highest weights were assigned to doline susceptibility (0.3723), followed by flooding hazard (0.1936), slope percentage (0.182) and geotechnical characteristics of the soils (0.1666).

The main difference observed is the decrease in suitability in the low terraces and flood plain, due to the highest doline susceptibility values in these areas. The more suitable areas are, more or less, the same as in the suitability analysis under more sustainable objectives (Map 62).

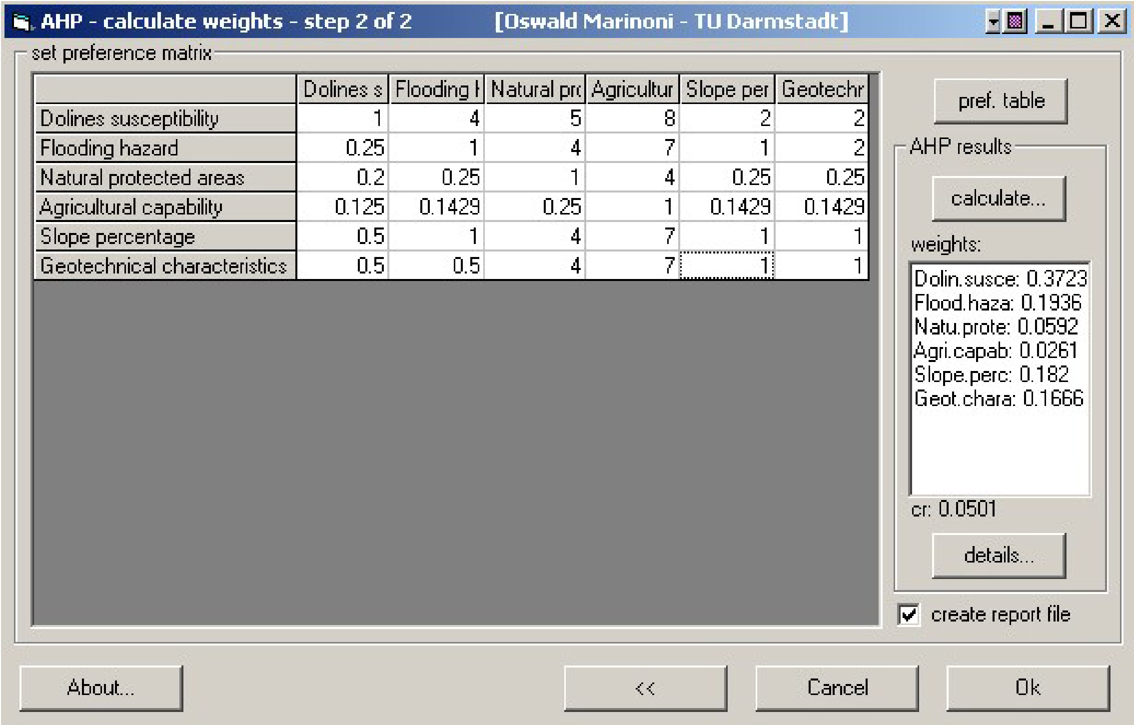


Figure 65: Pairwise comparison matrix, criterion weights and consistency ratio for urban location under economic aspects.

6.1.4.5. Potential conflicts between stakeholders

Map 63 shows the results of the potential conflicts analysis for new urban areas. In this case, both approaches yielded similar results for the most suitable areas, with respect to the sustainability and economical aspects. Thus, the best places for locating new urban areas are the places mentioned above, which, in the case of the south of Zaragoza, correspond to new urban developing areas.

6.1.5. Detection of land-use conflicts

It is possible take the support of land-use decision process one step further by searching for areas where there is a conflict between land uses. Map 64 shows the results of this approach. A summation of all the suitability maps under the geoscientific aspect, which implies sustainable development, was performed. This first of the threeapproaches was selected to carry out the summation, since it was our opinion that the potential conflicts between stakeholders approach should only be performed in case of grave, irresolvable conflicts.

The areas with the highest land-use conflicts are shown in red. These correspond to the high terraces and pediments, mainly at the south-west of Zaragoza, where, in general, geo-hazards (groundwater vulnerability, doline and erosion susceptibility) show the lowest values, and many geo-resources (sand and gravel and good agricultural soils) also exist. In addition, these sectors have low slope percentages, which is a limiting variable for many uses, and a lack of natural spaces of great environmental values.

In fact, at present, these areas are developing very fast in the proximity of Zaragoza, with the construction of a great industrial area (PLAZA) and several urban areas. Nevertheless, the pediment sector is characterized by a lack of geological, hydrogeological and geotechnical information, which determined the debatable good quality of the models in this sector. Thus, it is recommended to continue the research in this direction, since more borehole information should be available, in view of the current construction activities in the new industrial and urban areas and for the High-velocity railway.

6.2. Site selection analysis

The main objective of a site selection analysis is the ranking of feasible alternatives (see chapter 2.3.4.). Generally, *outranking methods*, as *PROMETHEE-2*, require pairwise or global comparisons among alternatives. Therefore, they are regarded as impractical for applications where the number of alternatives is large (Joerin *et al*., 2001; Marinoni, 2005; Pereira and Duckstein, 1993; Tkach and Simonovic, 1997). Thus, future alternatives of the different land uses should be defined and digitalized.

Criteria must be defined, but due to the outranking nature of the method used, *PROMETHEE-2*, these criteria should not be transformed or standardized, and may be left in their own units (Figure 66). The criteria are the same used for the site search analysis. However, the impossibility of superimposing the constraints to the final result determined their introduction as an additional criterion.

Since the criteria are not standardized, it is important to define whether an increase in the value of a determined criterion implies an improvement or decrease in land-use suitability. In addition, as every alternative is composed of several criteria values (pixels in the criteria layers) and *PROMETHEE-2* only admits a single value, the criteria values for every alternative should be defined. The tool developed by Oswald Marinoni offers several alternatives: minimum, maximum, mean, mean plus one or two standard deviations and mean minus one or two standard deviations value. The mean value was selected for all the criteria. In our opinion, this value is a better representation of all alternative values. Minimum and maximum values are usually rare events with a low probability of occurrence.

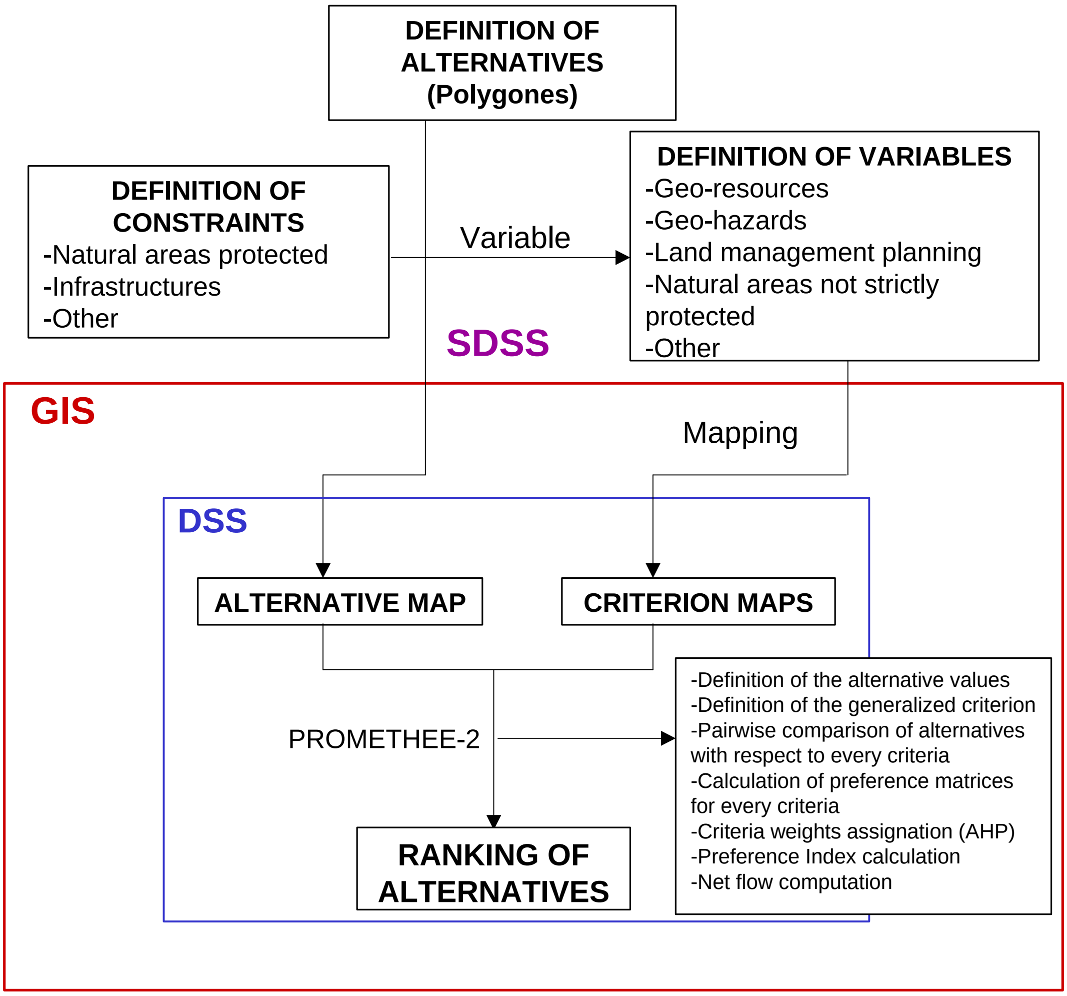


Figure 66: Scheme for the site selection analysis.

As mentioned above, the basic principle of this decision-aid methodology is based on a pairwise comparison of alternatives along each recognised criterion. Thus, the preference or not of one alternative respect to another, which is a function of the difference between two alternatives, must be established by defining the generalized criterion. Brans *et al*. (1984) proposed six different types of preference functions to define the generalized criterion (Figure 67):

- *Usual Criterion*: the preference, *H (d),* is 0 when there are no differences in the values of the alternatives to be compared. In the case of difference, *d,* between alternatives, *d* > 0, the preference is 1.

- *Quasi-criterion*: in this case the indifference threshold, *q,* should be defined. It is the largest value of *d* below which the decision-maker considers that there is indifference. The preference is 0 if $d \leq q$, and 1 in the rest of cases.

- *Criterion with linear preference*: the preference value and *d* follow a linear function. The strict preference threshold, *p,* should be defined. It represents the lowest value of d above which the decision-maker considers that there is strict preference. The preference value might be any possible value between 0, no preference, and 1, strict preference.

- *Level-criterion*: there exist three levels of preference. The parameters *q* and *p* should be defined. The preference is 0 if $d \leq q$, 0.5 if *d* is between the thresholds *q* and *p,* and 1 if *d* is higher than *p.*

- *Criterion with linear preference and indifference area:* this preference function is the same as the criterion with linear difference, but the parameter *q* should be also defined and introduced.

- *Gaussian Criterion:* the parameter σ, which is directly connected to the standard deviation of a normal distribution, should be defined.

All these generalized criteria are implemented in the tool developed by Oswald Marinoni. However, in our case, the *Usual Criterion* was selected to define the preference between alternatives.

The pair comparison of alternatives produces the preference matrix for each criterion. After having calculated the preference matrices along each criterion, a first aggregation is performed by multiplying each preference value, *P*, by a weighting factor, *w* (expressing the weight or importance of a criterion), and building the sum of these products (Marinoni, 2005). This results in a preference index, Π (Figure 68). The *Analytical Hierarchy Process* has also been integrated in this tool and used for criteria weighting.

The final ranking of alternatives is performed by calculating the net flow $\Phi(a_1)$ for every alternative, *a*, which is a subtraction between the leaving flow and the entering flow (Brans *et al*., 1984). The higher the net flow, the higher the preference of an alternative over the others (Table 51). The leaving flow $\Phi^+(a_1)$ represents a measure of the outranking character of a_1 (how a_1 is outranking all the other alternatives). Symmetrically, the entering flow $\Phi^-(a_1)$ is giving the outranked character of a_1 (how a_1 is dominated by all the other actions).

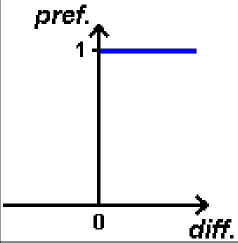
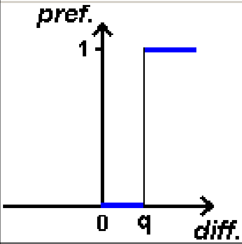
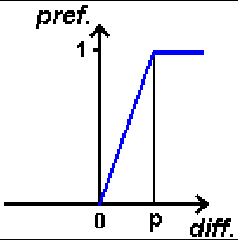
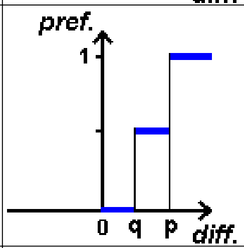
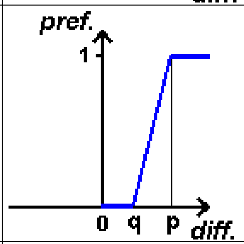
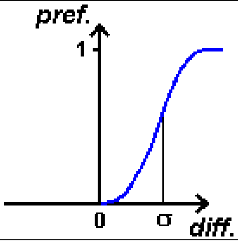
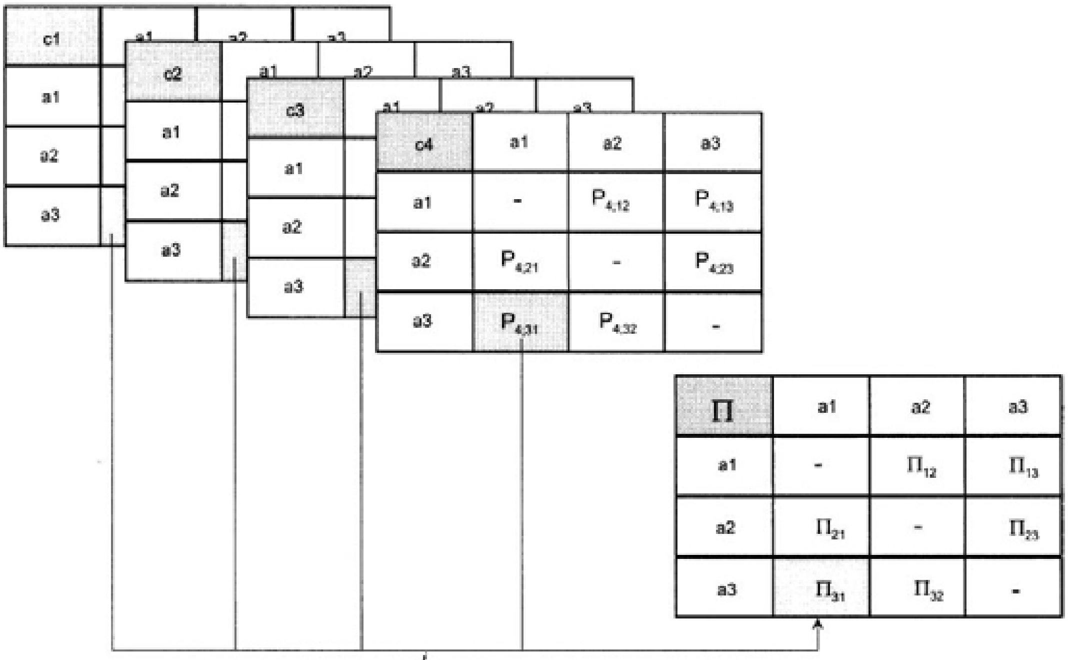
Type of generalized criterion	Analytical definition	Shape	Parameters to define
Usual criterion	H (d) = 0 if d = 0 H (d) = 1 if d > 0		
Quasi-criterion	H (d) = 0 if d ? q H (d) = 1 if d > q		q
Criterion with linear preference	H (d) = d/p if d ? p H (d) = 1 if d > p		p
Level-criterion	H (d) = 0 if d ? q H (d) = 1/2 if q < d ? p H (d) = 1 if d > p		q,p
Criterion with linear preference and indifference area	H (d) = 0 if d ? q H (d) = d-q/p-q if q < d ? p H (d) = 1 if d > p		q,p
Gaussian-criterion	H (d) = 1 – esp (- d^2 / $2\sigma^2$)		σ

Figure 67: Generalized criteria (after Brans *et al*., 1984). The function graphics presented (shape) are included in the tool developed by Oswald Marinoni.



$$\Pi_{31} = \sum_{i=1}^{j} w_i P_{i;31}$$

Figure 68: Schematic calculation of the preference index Π. Source: Marinoni (2005).

Table 51: Example of possible preference indices, leaving, entering and net flow calculations and final ranking. After Marinoni (2005).

Π	a1	a2	a3	$\Phi^+(a_x)$	$\Phi(a_x)$	Rank
a1	-	0.25	0.75	1.0	0	2
a2	0.75	-	0.75	1.5	1	1
a3	0.25	0.25	-	0.5	-1	3
$\Phi^-(a_x)$	1	0.5	1.5			

6.2.1. Sand and gravel extractions

The alternatives are represented by real future extraction sites, which were supported by the Environmental Department of Zaragoza Council (Map 65). However, due to the reduced number of real alternatives (only three), it was decided to improve the number of feasible sites up to twelve by adding imaginary alternatives.

As mentioned above, criteria are introduced in the site selection analysis with their original values. However, as explained in chapter 6.1.1.3., it is absolutely necessary to give a value to the area outside the models which do not cover the whole study area. These values have been selected more or less arbitrarily. As the generalized criterion used is *Usual Criterion, simple difference*, the value selected is not very important. It should only be higher or lower than the rest of values in the model, representing higher or lower suitability.

In the case of sand and gravel extractions, an increase in the value of all criteria, with the exception of overburden thickness, implies a suitability improvement.

Thus, the values for groundwater protection and water table depth outside the model were higher than the maximum found in the model (Map 65). In the case of resource thickness, value 0 was assigned to areas outside the model in the Tertiary sediments, and value 15 m was assigned to the old terraces disconnected from the aquifer, according to chapter 6.1.1.3. In the overburden thickness variable, as there is no resource outside the model area, the suitability is reduced in this sector. Thus, the greatest thickness value, fifty-five, was assigned there, as the suitability decreases with an increase in the variable value.

The criterion representing the constraints should be also introduced. It was reclassified into two different values, zero in the area where extraction is forbidden or not possible due to the presence of other uses, and one in areas where this use is permitted or possible.

As a consequence of the introduction of a new criterion (constraints), the criteria weights should be recalculated using the *Analytical Hierarchy Process*. Table 52 shows the preference matrix and criteria weights, with a consistency ratio of 0.0293, of the site search analysis for sand and gravel extraction sites. The criteria for preference assignation are the same as for the site search analysis under the concept of sustainability, but the constraints achieve the highest preference and, as a consequence, weight, in order to avoid the outranking of alternatives located in forbidden areas.

Table 53 shows the preference indices and the leaving and entering flow. Alternatives 1, 2 and 3 are the real ones supported by Zaragoza Council. Map 65 shows the location of the alternatives, the criteria original values and the results of the site selection analysis for the location of new sand and gravel extraction sites. With the exception of alternative 3, the real alternatives present good suitability ranking values. The low rank of alternative 3 may be caused by the low resource thickness and high overburden values of the models in this sector. It is important to remark the similarity of the site selection analysis and the site search analysis results. The higher ranking positions are found in alternatives located on the high terraces and pediments covering these terraces, where the site search analysis also gave the highest suitability values.

Table 52: Preference values and criteria weights for sand and gravel extraction site selection analysis.

Preference matrix	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Weight**
A.Distance to extractions	1.00	0.20	0.14	0.33	0.14	0.50	0.13	0.20	1.00	0.11	0.018
B.Groundwater depth	5.00	1.00	0.50	4.00	0.50	4.00	0.33	1.00	5.00	0.20	0.079
C.Groundwater protection	7.00	2.00	1.00	6.00	1.00	6.00	0.50	2.00	7.00	0.33	0.131
D.Distance to nuclei	3.00	0.25	0.17	1.00	0.17	2.00	0.14	0.25	3.00	0.13	0.032
E.Distance to natural areas	7.00	2.00	1.00	6.00	1.00	6.00	0.50	2.00	7.00	0.33	0.131
F.Distance to roads	2.00	0.25	0.17	0.50	0.17	1.00	0.14	0.25	2.00	0.13	0.025
G.Resource thickness	8.00	3.00	2.00	7.00	2.00	7.00	1.00	3.00	8.00	0.50	0.195
H.Irrigation capacity of soil	5.00	1.00	0.50	4.00	0.50	4.00	0.33	1.00	5.00	0.20	0.079
I.Overburden thickness	1.00	0.20	0.14	0.33	0.14	0.50	0.13	0.20	1.00	0.11	0.018
J.Constraints	9.00	5.00	3.00	8.00	3.00	8.00	2.00	5.00	9.00	1.00	0.292

Table 53: Preference indices and entering and leaving flow for sand and gravel extraction alternatives.

Π	1	2	3	4	5	6	7	8	9	10	11	12	Φ^+
1	-	0.48	0.48	0.54	0.35	0.85	0.54	0.69	0.35	0.54	0.56	0.69	6.068
2	0.31	-	0.35	0.54	0.64	0.85	0.54	0.56	0.32	0.54	0.58	0.69	5.913
3	0.31	0.15	-	0.32	0.54	0.66	0.35	0.65	0.10	0.24	0.36	0.65	4.315
4	0.46	0.17	0.39	-	0.44	0.85	0.40	0.58	0.17	0.02	0.50	0.53	4.496
5	0.65	0.36	0.47	0.48	-	0.98	0.46	0.69	0.34	0.32	0.63	0.56	5.951
6	0.15	0.15	0.34	0.15	0.02	-	0.18	0.42	0.04	0.02	0.04	0.38	1.885
7	0.46	0.17	0.36	0.23	0.46	0.82	-	0.52	0.36	0.23	0.39	0.42	4.416
8	0.31	0.15	0.06	0.13	0.31	0.50	0.19	-	0.04	0.00	0.21	0.18	2.071
9	0.65	0.39	0.61	0.46	0.58	0.96	0.27	0.67	-	0.24	0.48	0.67	5.993
10	0.46	0.17	0.47	0.69	0.68	0.98	0.48	0.71	0.47	-	0.71	0.69	6.489
11	0.44	0.13	0.34	0.13	0.29	0.96	0.24	0.50	0.15	0.00	-	0.53	3.724
12	0.31	0.02	0.06	0.17	0.44	0.55	0.29	0.45	0.04	0.02	0.17	-	2.509
Φ^-	4.51	2.33	3.93	3.85	4.73	8.96	3.93	6.44	2.36	2.17	4.62	6.00	

6.2.2. Irrigated areas

The alternatives are possible future irrigation areas, according to the Hydrologic Planning supported by CHE (**http://oph.chebro.es/ContenidoCartoRegadios.htm**). In the case of future development of the needed infrastructures and demands by society for new irrigated land, ten possible irrigation areas are planned for the study area (Map 66).

An increase in original value for doline susceptibility, slope percentage and elevation above sea level variables leads to a decrease in suitability. Thus, in the doline susceptibility model the area outside the model is given the lowest value, zero. In contrast, in the groundwater protection model, where higher original value implies an increased suitability, the area outside the model was assigned the highest value (Map 66).

Table 54 shows the preference matrix and criteria weights, with a consistency ratio of 0.0368, of the site search analysis for irrigation areas. In this case, the constraints also obtain the highest weight.

Table 55 shows the preference indices and the leaving and entering flow, and Map 66 shows the location of the alternatives, the criteria original values and the results of the site selection analysis. The highest rankings are also located in the pediment sector south-west of Zaragoza city. The lowest ones correspond to the locations in areas where some constraints are present. Here also, the results of the site selection analysis are similar to the site search analysis.

Table 54: Preference values and criteria weights for sand and gravel extraction site selection analysis.

Preference matrix	A	B	C	D	E	F	G	H	Weight
A.Elevation above sea level	1.00	0.20	0.14	0.14	0.50	0.33	0.17	0.13	0.022
B.Change in erosion	5.00	1.00	0.25	0.25	4.00	3.00	0.33	0.20	0.076
C.Groundwater protection	7.00	4.00	1.00	1.00	6.00	5.00	2.00	0.50	0.199
D.Location of natural areas	7.00	4.00	1.00	1.00	6.00	5.00	2.00	0.50	0.199
E.Slope percentage	2.00	0.25	0.17	0.17	1.00	0.50	0.20	0.14	0.030
F.Irrigation capability of soils	3.00	0.33	0.20	0.20	2.00	1.00	0.25	0.17	0.043
G.Doline susceptibility	6.00	3.00	0.50	0.50	5.00	4.00	1.00	0.33	0.133
H.Constraints	8.00	5.00	2.00	2.00	7.00	6.00	3.00	1.00	0.300

Table 55: Preference indices and entering and leaving flow for sand and gravel extraction alternatives.

Π	1	2	3	4	5	6	7	8	9	10	Φ^+
1	-	0.30	0.71	0.60	0.41	0.63	0.22	0.41	0.33	0.33	3.932
2	0.37	-	0.91	0.34	0.41	0.71	0.22	0.41	0.33	0.41	4.094
3	0.29	0.09	-	0.26	0.33	0.35	0.26	0.43	0.33	0.33	2.688
4	0.27	0.53	0.74	-	0.41	0.63	0.00	0.41	0.33	0.33	3.644
5	0.59	0.59	0.67	0.59	-	0.37	0.29	0.30	0.22	0.22	3.842
6	0.37	0.29	0.65	0.37	0.64	-	0.29	0.30	0.33	0.33	3.564
7	0.65	0.65	0.74	0.87	0.71	0.71	-	0.71	0.63	0.71	6.359
8	0.59	0.59	0.57	0.59	0.70	0.70	0.29	-	0.33	0.36	4.742
9	0.67	0.67	0.67	0.67	0.78	0.67	0.37	0.67	-	0.44	5.598
10	0.67	0.59	0.67	0.67	0.78	0.67	0.29	0.64	0.56	-	5.543
Φ^-	4.47	4.31	6.31	4.96	5.16	5.44	2.24	4.26	3.40	3.46	

6.2.3. Industrial settlements

The alternatives are represented by the industrial areas included in the IAF database (see chapter 6.1.1.1.), which have free space for the establishment of new factories (See Map 48 and 67). A total of twenty seven industrial areas were included here for the site selection analysis.

An increase in the original value for doline susceptibility and slope percentage leads to a decrease in suitability. In contrast, for the remaining alternatives an increase in variable values leads to an increased suitability. Thus, in the doline susceptibility model the area outside the model receives the lowest value, zero. In the groundwater protection model and flooding hazard, to the area outside the models is assigned the highest value (Map 67).

Table 56 shows the preference matrix and criteria weights, with a consistency ratio of 0.0256, for the site search analysis for industrial settlements. The values are similar to the site search analysis with the addition of the constraints, which present the highest preference value. The preference indices and the leaving and entering flow are presented in Tables 57a and 57b. Finally, Map 67 shows the location of the alternatives, the criteria original values and the results of the site selection analysis. The best alternatives are generally located south of Zaragoza city, outside the alluvial sector. In contrast, the worst locations are the alluvial areas in the surroundings of El

Burgo de Ebro, the industrial areas in the north of Zaragoza city, and the *Logroño* Corridor, upstream of Zaragoza.

Table 56: Preference values and criteria weights for industrial settlements site selection analysis.

Preference matrix	A	B	C	D	E	F	G	H	Weight
A.Groundwater protection	1.00	2.00	3.00	1.00	5.00	8.00	6.00	0.50	0.197
B.Doline susceptibility	0.50	1.00	2.00	0.50	3.00	7.00	4.00	0.33	0.121
C.Flooding hazard	0.33	0.50	1.00	0.33	2.00	6.00	3.00	0.25	0.087
D.Location of natural areas	1.00	2.00	3.00	1.00	5.00	8.00	6.00	0.50	0.197
E.Agricultural capability of soils	0.20	0.33	0.50	0.20	1.00	4.00	2.00	0.17	0.048
F.Slope percentage	0.13	0.14	0.17	0.13	0.25	1.00	0.50	0.11	0.020
G.Geotechnical characteristics	0.17	0.25	0.20	0.17	0.50	2.00	1.00	0.14	0.030
H.Constraints	2.00	3.00	4.00	2.00	6.00	9.00	7.00	1.00	0.300

Table 57a: Preference indices and entering and leaving flow for industrial settlement alternatives.

Π	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	-	0.45	0.75	0.67	0.75	0.47	0.27	0.47	0.47	0.67	0.67	0.75	0.37	0.22
2	0.55	-	0.44	0.55	0.32	0.32	0.25	0.35	0.37	0.32	0.32	0.35	0.12	0.25
3	0.22	0.37	-	0.67	0.32	0.07	0.27	0.47	0.49	0.37	0.17	0.30	0.17	0.22
4	0.33	0.45	0.33	-	0.41	0.02	0.25	0.67	0.39	0.39	0.32	0.31	0.32	0.25
5	0.25	0.45	0.44	0.60	-	0.37	0.30	0.47	0.49	0.49	0.07	0.42	0.17	0.25
6	0.53	0.45	0.74	0.89	0.41	-	0.25	0.67	0.69	0.67	0.32	0.74	0.32	0.25
7	0.74	0.75	0.74	0.67	0.71	0.67	-	0.67	0.67	0.67	0.62	0.74	0.67	0.71
8	0.53	0.42	0.33	0.25	0.30	0.02	0.25	-	0.02	0.22	0.22	0.33	0.34	0.25
9	0.53	0.41	0.31	0.53	0.28	0.00	0.25	0.62	-	0.32	0.20	0.31	0.32	0.25
10	0.33	0.45	0.44	0.53	0.28	0.02	0.25	0.47	0.37	-	0.00	0.42	0.12	0.25
11	0.33	0.45	0.63	0.60	0.71	0.37	0.30	0.47	0.49	0.69	-	0.61	0.37	0.25
12	0.22	0.45	0.42	0.69	0.34	0.07	0.27	0.47	0.49	0.39	0.19	-	0.17	0.22
13	0.63	0.65	0.63	0.60	0.60	0.37	0.25	0.35	0.37	0.57	0.32	0.63	-	0.55
14	0.78	0.75	0.78	0.67	0.75	0.67	0.08	0.67	0.67	0.67	0.67	0.78	0.37	-
15	0.53	0.33	0.33	0.76	0.28	0.27	0.25	0.55	0.57	0.27	0.22	0.31	0.32	0.25
16	0.33	0.41	0.33	0.34	0.42	0.02	0.25	0.12	0.14	0.34	0.14	0.12	0.12	0.25
17	0.53	0.41	0.33	0.34	0.41	0.02	0.25	0.32	0.14	0.34	0.34	0.31	0.32	0.25
18	0.23	0.45	0.31	0.17	0.41	0.05	0.00	0.37	0.37	0.37	0.32	0.31	0.32	0.00
19	0.53	0.45	0.45	0.53	0.41	0.14	0.22	0.37	0.39	0.34	0.32	0.44	0.32	0.22
20	0.53	0.41	0.33	0.52	0.28	0.02	0.25	0.50	0.22	0.22	0.20	0.31	0.32	0.25
21	0.53	0.45	0.33	0.60	0.30	0.07	0.25	0.55	0.37	0.27	0.22	0.61	0.37	0.25
22	0.83	0.75	0.75	0.91	0.71	0.37	0.25	0.67	0.69	0.69	0.64	0.74	0.37	0.55
23	0.65	0.48	0.75	0.89	0.74	0.72	0.25	0.70	0.72	0.70	0.65	0.74	0.35	0.44
24	0.53	0.45	0.44	0.59	0.41	0.37	0.30	0.37	0.39	0.37	0.37	0.44	0.37	0.25
25	0.75	0.75	0.75	0.67	0.75	0.67	0.35	0.67	0.67	0.67	0.67	0.75	0.67	0.74
26	0.78	0.75	0.78	0.67	0.75	0.67	0.35	0.67	0.67	0.67	0.67	0.78	0.67	0.74
27	0.95	0.78	0.74	0.89	0.74	0.70	0.30	0.70	0.72	0.70	0.70	0.74	0.70	0.55
Φ^-	13.69	13.41	13.65	15.76	12.77	7.48	6.42	13.31	11.97	12.30	9.49	13.30	8.99	8.61

Table 57b: Preference indices and entering and leaving flow for industrial settlements alternatives.

Π	15	16	17	18	19	20	21	22	23	24	25	26	27	Φ^+
1	0.47	0.67	0.47	0.77	0.47	0.47	0.47	0.17	0.35	0.47	0.22	0.22	0.05	12.22
2	0.47	0.40	0.40	0.55	0.35	0.40	0.32	0.02	0.32	0.32	0.25	0.25	0.22	8.74
3	0.47	0.47	0.47	0.69	0.35	0.47	0.47	0.05	0.05	0.37	0.22	0.22	0.27	8.62
4	0.15	0.58	0.58	0.83	0.38	0.40	0.32	0.00	0.02	0.32	0.25	0.25	0.02	8.50
5	0.52	0.38	0.40	0.60	0.40	0.52	0.47	0.07	0.07	0.37	0.25	0.25	0.27	9.28
6	0.45	0.70	0.70	0.95	0.58	0.70	0.62	0.32	0.00	0.32	0.25	0.25	0.22	12.93
7	0.67	0.67	0.67	1.00	0.70	0.67	0.67	0.67	0.67	0.62	0.25	0.25	0.62	17.08
8	0.17	0.55	0.35	0.63	0.35	0.17	0.14	0.02	0.02	0.32	0.25	0.25	0.22	6.91
9	0.15	0.53	0.53	0.63	0.33	0.45	0.32	0.00	0.00	0.30	0.25	0.25	0.20	8.25
10	0.45	0.38	0.38	0.63	0.38	0.50	0.42	0.00	0.02	0.32	0.25	0.25	0.22	8.11
11	0.50	0.58	0.38	0.68	0.40	0.52	0.47	0.05	0.07	0.32	0.25	0.25	0.22	10.92
12	0.49	0.69	0.49	0.69	0.37	0.49	0.19	0.07	0.07	0.37	0.22	0.22	0.27	8.96
13	0.40	0.60	0.40	0.68	0.40	0.40	0.32	0.32	0.37	0.32	0.25	0.25	0.22	11.42
14	0.67	0.67	0.67	1.00	0.70	0.67	0.67	0.37	0.47	0.67	0.05	0.05	0.37	15.29
15	-	0.55	0.55	0.83	0.60	0.57	0.20	0.22	0.02	0.32	0.25	0.25	0.41	9.97
16	0.17	-	0.02	0.33	0.05	0.14	0.12	0.02	0.02	0.02	0.25	0.25	0.22	4.93
17	0.17	0.53	-	0.33	0.35	0.14	0.12	0.02	0.02	0.32	0.25	0.25	0.22	7.00
18	0.17	0.67	0.67	-	0.38	0.37	0.32	0.00	0.00	0.30	0.05	0.05	0.00	6.63
19	0.12	0.67	0.37	0.62	-	0.37	0.32	0.12	0.02	0.32	0.25	0.25	0.22	8.74
20	0.15	0.53	0.53	0.63	0.35	-	0.20	0.00	0.02	0.32	0.25	0.25	0.22	7.78
21	0.52	0.60	0.60	0.68	0.40	0.52	-	0.02	0.07	0.32	0.25	0.25	0.22	9.58
22	0.50	0.70	0.70	1.00	0.60	0.72	0.67	-	0.37	0.32	0.25	0.25	0.22	15.16
23	0.70	0.70	0.70	1.00	0.70	0.70	0.65	0.35	-	0.67	0.25	0.25	0.41	15.82
24	0.40	0.40	0.40	0.70	0.40	0.40	0.37	0.37	0.05	-	0.25	0.25	0.41	9.98
25	0.67	0.67	0.67	0.95	0.67	0.67	0.67	0.67	0.67	0.67	-	0.50	0.67	17.63
26	0.67	0.67	0.67	0.95	0.67	0.67	0.67	0.67	0.67	0.67	0.10	-	0.67	17.32
27	0.50	0.70	0.70	1.00	0.70	0.70	0.70	0.70	0.50	0.50	0.25	0.25	-	17.04
Φ^-	10.74	15.17	13.40	19.37	11.97	12.74	10.83	5.25	4.90	10.13	5.78	6.18	7.22	

6.2.4. Urban development

The areas classified as developing areas, according to the Land Management Planning of Zaragoza city, represent the alternatives in the site selection analysis for new urban areas. A total of forty areas were included in this analysis.

As mentioned above, the variables correspond to those for the location of industrial settlements, with the exception of groundwater protection. Thus, these variables present similar characteristics (Map 68). However, their weights change slightly. Table 58 shows the preference matrix and criteria weights, with a consistency ratio of 0.0256, of the site search analysis for urban development. The preference indices and the leaving and entering flows are presented in Tables 59a and 59b. And finally, Map 68 shows the location of the alternatives, the criteria original values and the results of the site selection analysis. The first rankings, alternatives 40, 18, 12 and 13, are located south-west and south-east of the present-day city of Zaragoza.

Table 58: Preference values and criteria weights for urban development site selection analysis.

Preference matrix	A	B	C	D	E	F	G	H	Weight
B.Doline susceptibility	0.50	1.00	2.00	0.50	3.00	7.00	4.00	0.33	0.161
C.Flooding hazard	0.33	0.50	1.00	0.33	2.00	6.00	3.00	0.25	0.106
D.Location of natural areas	1.00	2.00	3.00	1.00	5.00	8.00	6.00	0.50	0.242
E.Agricultural capability of soils	0.20	0.33	0.50	0.20	1.00	4.00	2.00	0.17	0.068
F.Slope percentage	0.13	0.14	0.17	0.13	0.25	1.00	0.50	0.11	0.024
G.Geotechnical characteristics	0.17	0.25	0.20	0.17	0.50	2.00	1.00	0.14	0.043
H.Constraints	2.00	3.00	4.00	2.00	6.00	9.00	7.00	1.00	0.356

Table 59a: Preference indices and entering and leaving flow for urban development alternatives.

Π	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-	0.07	0.16	0.09	0.19	0.02	0.19	0.19	0.25	0.02	0.02	0.27	0.27	0.27	0.07	0.38	0.27	0.07	0.45	0.02
2	0.59	-	0.16	0.45	0.25	0.02	0.19	0.16	0.61	0.19	0.19	0.27	0.27	0.27	0.14	0.69	0.27	0.02	0.45	0.38
3	0.45	0.49	-	0.45	0.61	0.45	0.25	0.45	0.45	0.02	0.09	0.27	0.27	0.69	0.14	0.73	0.33	0.07	0.45	0.45
4	0.52	0.20	0.16	-	0.16	0.02	0.19	0.16	0.25	0.19	0.19	0.27	0.27	0.27	0.07	0.38	0.27	0.07	0.59	0.19
5	0.42	0.40	0.00	0.45	-	0.02	0.02	0.00	0.45	0.02	0.02	0.27	0.27	0.62	0.07	0.73	0.27	0.07	0.42	0.38
6	0.59	0.63	0.16	0.59	0.59	-	0.19	0.16	0.61	0.19	0.19	0.27	0.27	0.69	0.14	0.89	0.27	0.07	0.59	0.54
7	0.42	0.47	0.36	0.42	0.59	0.42	-	0.42	0.45	0.00	0.00	0.24	0.24	0.69	0.14	0.73	0.27	0.04	0.42	0.42
8	0.42	0.49	0.16	0.45	0.61	0.45	0.19	-	0.45	0.02	0.02	0.27	0.27	0.69	0.14	0.73	0.27	0.07	0.45	0.38
9	0.36	0.04	0.16	0.36	0.16	0.00	0.16	0.16	-	0.00	0.00	0.24	0.24	0.27	0.07	0.31	0.27	0.04	0.36	0.00
10	0.63	0.47	0.56	0.47	0.63	0.47	0.65	0.63	0.65	-	0.09	0.27	0.27	0.69	0.14	0.73	0.33	0.07	0.47	0.47
11	0.63	0.47	0.56	0.47	0.63	0.47	0.65	0.63	0.65	0.56	-	0.31	0.31	0.73	0.49	0.73	0.38	0.04	0.47	0.47
12	0.63	0.63	0.63	0.63	0.63	0.63	0.65	0.63	0.65	0.63	0.59	-	0.59	0.85	0.65	0.65	0.85	0.63	0.63	0.63
13	0.63	0.63	0.63	0.63	0.63	0.63	0.65	0.63	0.65	0.63	0.59	0.31	-	0.73	0.49	0.89	0.38	0.63	0.63	0.63
14	0.63	0.63	0.20	0.63	0.27	0.20	0.20	0.20	0.63	0.20	0.16	0.04	0.16	-	0.27	0.63	0.00	0.20	0.63	0.56
15	0.59	0.52	0.52	0.59	0.59	0.52	0.52	0.52	0.59	0.52	0.16	0.24	0.40	0.62	-	0.85	0.27	0.16	0.59	0.52
16	0.52	0.20	0.16	0.52	0.16	0.00	0.16	0.16	0.59	0.16	0.16	0.24	0.00	0.27	0.04	-	0.24	0.04	0.59	0.52
17	0.63	0.63	0.56	0.63	0.63	0.63	0.63	0.63	0.63	0.56	0.52	0.04	0.52	0.73	0.63	0.65	-	0.56	0.63	0.63
18	0.59	0.63	0.52	0.59	0.59	0.59	0.61	0.59	0.61	0.52	0.61	0.27	0.27	0.69	0.49	0.85	0.33	-	0.59	0.59
19	0.16	0.20	0.16	0.02	0.19	0.02	0.19	0.16	0.25	0.19	0.19	0.27	0.27	0.27	0.07	0.31	0.27	0.07	-	0.02
20	0.59	0.27	0.16	0.42	0.23	0.07	0.19	0.23	0.61	0.19	0.19	0.27	0.27	0.33	0.14	0.38	0.27	0.07	0.59	-
21	0.59	0.27	0.16	0.61	0.23	0.09	0.25	0.23	0.61	0.19	0.25	0.27	0.27	0.33	0.14	0.85	0.33	0.07	0.59	0.61
22	0.59	0.47	0.52	0.45	0.61	0.45	0.61	0.59	0.61	0.54	0.61	0.27	0.27	0.69	0.49	0.69	0.33	0.42	0.42	0.45
23	0.25	0.25	0.19	0.25	0.25	0.25	0.25	0.25	0.25	0.19	0.19	0.27	0.43	0.33	0.09	0.50	0.33	0.19	0.25	0.25
24	0.59	0.59	0.52	0.59	0.59	0.59	0.54	0.59	0.61	0.52	0.52	0.24	0.24	0.69	0.45	0.85	0.27	0.36	0.59	0.52
25	0.52	0.16	0.16	0.52	0.16	0.16	0.19	0.16	0.54	0.16	0.16	0.24	0.24	0.27	0.02	0.43	0.27	0.00	0.52	0.16
26	0.59	0.52	0.52	0.59	0.59	0.52	0.54	0.52	0.61	0.52	0.16	0.27	0.27	0.62	0.02	0.85	0.27	0.00	0.59	0.52
27	0.25	0.25	0.19	0.25	0.25	0.25	0.19	0.25	0.25	0.19	0.19	0.27	0.02	0.33	0.09	0.25	0.27	0.19	0.61	0.25
28	0.59	0.20	0.16	0.59	0.23	0.16	0.19	0.16	0.25	0.16	0.16	0.24	0.24	0.27	0.07	0.54	0.27	0.04	0.59	0.16
29	0.61	0.65	0.54	0.61	0.61	0.61	0.54	0.54	0.61	0.19	0.19	0.27	0.27	0.69	0.14	0.89	0.27	0.07	0.61	0.54
30	0.59	0.54	0.52	0.61	0.61	0.54	0.54	0.54	0.61	0.54	0.19	0.27	0.27	0.62	0.38	0.85	0.27	0.02	0.61	0.54
31	0.61	0.45	0.52	0.45	0.61	0.45	0.54	0.54	0.61	0.38	0.02	0.27	0.27	0.69	0.45	0.69	0.27	0.02	0.45	0.38
32	0.59	0.61	0.16	0.61	0.61	0.09	0.19	0.16	0.61	0.19	0.19	0.27	0.27	0.69	0.09	0.85	0.27	0.02	0.61	0.54
33	0.61	0.61	0.54	0.61	0.61	0.45	0.54	0.54	0.61	0.54	0.54	0.27	0.27	0.69	0.45	0.69	0.27	0.38	0.61	0.54
34	0.59	0.59	0.16	0.42	0.59	0.09	0.19	0.16	0.61	0.19	0.19	0.27	0.27	0.69	0.09	0.69	0.27	0.02	0.59	0.38
35	0.07	0.04	0.00	0.07	0.23	0.00	0.19	0.00	0.09	0.02	0.02	0.27	0.27	0.27	0.07	0.38	0.27	0.07	0.07	0.02
36	0.47	0.47	0.56	0.47	0.63	0.47	0.58	0.63	0.49	0.42	0.02	0.31	0.27	0.69	0.49	0.73	0.27	0.07	0.47	0.47
37	0.27	0.11	0.20	0.11	0.27	0.11	0.30	0.27	0.30	0.07	0.14	0.31	0.31	0.38	0.14	0.38	0.38	0.07	0.11	0.14
38	0.27	0.27	0.20	0.27	0.27	0.27	0.23	0.20	0.30	0.20	0.19	0.31	0.27	0.38	0.14	0.54	0.31	0.20	0.27	0.20
39	0.63	0.47	0.56	0.47	0.63	0.47	0.58	0.56	0.65	0.56	0.23	0.31	0.31	0.73	0.49	0.73	0.31	0.04	0.47	0.40
40	0.63	0.63	0.56	0.63	0.63	0.63	0.63	0.63	0.63	0.52	0.23	0.24	0.24	0.69	0.49	0.89	0.33	0.20	0.63	0.63
Φ^-	19.82	16.20	12.90	17.98	17.49	12.27	14.25	14.21	19.86	11.06	8.32	9.99	10.61	21.10	9.13	25.52	11.56	5.43	19.57	15.48

Table 59b: Preference indices and entering and leaving flow for industrial settlements alternatives.

Π	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Φ^{+}
1	0.07	0.07	0.40	0.17	0.24	0.17	0.75	0.13	0.00	0.17	0.15	0.17	0.15	0.07	0.54	0.19	0.38	0.38	0.02	0.02	7.49
2	0.38	0.19	0.40	0.17	0.60	0.24	0.75	0.55	0.00	0.22	0.31	0.15	0.15	0.07	0.61	0.19	0.54	0.38	0.19	0.02	11.63
3	0.42	0.07	0.47	0.24	0.60	0.24	0.82	0.55	0.07	0.24	0.24	0.60	0.22	0.49	0.61	0.09	0.45	0.45	0.09	0.02	14.07
4	0.04	0.20	0.40	0.17	0.24	0.17	0.75	0.13	0.00	0.15	0.31	0.15	0.15	0.23	0.54	0.19	0.54	0.38	0.19	0.02	9.33
5	0.42	0.04	0.40	0.17	0.60	0.17	0.75	0.49	0.00	0.15	0.15	0.15	0.15	0.07	0.38	0.02	0.38	0.38	0.02	0.02	9.83
6	0.56	0.20	0.40	0.17	0.60	0.24	0.75	0.55	0.00	0.22	0.31	0.67	0.31	0.56	0.61	0.19	0.54	0.38	0.19	0.02	15.04
7	0.40	0.04	0.40	0.22	0.57	0.22	0.82	0.53	0.07	0.22	0.22	0.57	0.22	0.47	0.42	0.07	0.36	0.42	0.07	0.02	13.07
8	0.42	0.07	0.40	0.17	0.60	0.24	0.75	0.55	0.07	0.22	0.22	0.60	0.22	0.49	0.61	0.02	0.38	0.45	0.09	0.02	13.10
9	0.04	0.04	0.40	0.15	0.15	0.15	0.75	0.46	0.00	0.15	0.15	0.15	0.15	0.04	0.52	0.16	0.36	0.36	0.00	0.02	7.39
10	0.40	0.04	0.47	0.24	0.60	0.24	0.82	0.60	0.47	0.22	0.38	0.57	0.22	0.47	0.63	0.23	0.59	0.45	0.09	0.07	16.43
11	0.40	0.04	0.47	0.24	0.60	0.60	0.82	0.60	0.47	0.57	0.73	0.57	0.22	0.47	0.63	0.63	0.52	0.47	0.42	0.42	19.51
12	0.63	0.63	0.63	0.76	0.76	0.73	0.73	0.76	0.63	0.73	0.73	0.73	0.73	0.63	0.63	0.59	0.59	0.59	0.59	0.65	25.82
13	0.63	0.63	0.47	0.76	0.76	0.73	0.98	0.76	0.63	0.73	0.73	0.73	0.73	0.63	0.63	0.63	0.59	0.63	0.59	0.65	25.20
14	0.56	0.20	0.56	0.31	0.73	0.38	0.67	0.73	0.20	0.38	0.31	0.31	0.31	0.20	0.63	0.20	0.52	0.52	0.16	0.20	14.55
15	0.52	0.16	0.56	0.31	0.73	0.73	0.91	0.69	0.52	0.38	0.31	0.67	0.31	0.56	0.59	0.16	0.52	0.52	0.16	0.16	18.70
16	0.04	0.20	0.40	0.15	0.57	0.15	0.75	0.46	0.00	0.15	0.31	0.15	0.31	0.20	0.52	0.16	0.52	0.36	0.16	0.00	10.29
17	0.56	0.56	0.56	0.73	0.73	0.73	0.73	0.73	0.63	0.73	0.73	0.73	0.73	0.63	0.63	0.63	0.52	0.59	0.59	0.56	24.09
18	0.52	0.16	0.47	0.40	0.76	0.76	0.82	0.72	0.59	0.73	0.73	0.73	0.38	0.63	0.59	0.59	0.59	0.45	0.61	0.38	22.06
19	0.07	0.23	0.40	0.17	0.24	0.17	0.39	0.13	0.00	0.15	0.31	0.15	0.15	0.07	0.54	0.19	0.54	0.38	0.19	0.02	7.74
20	0.04	0.20	0.40	0.24	0.60	0.24	0.75	0.55	0.07	0.22	0.38	0.22	0.22	0.27	0.59	0.19	0.52	0.45	0.25	0.02	11.83
21	-	0.16	0.47	0.24	0.60	0.24	0.82	0.55	0.07	0.22	0.38	0.38	0.38	0.30	0.61	0.25	0.61	0.45	0.25	0.02	13.91
22	0.42	-	0.47	0.24	0.60	0.60	0.82	0.55	0.42	0.57	0.73	0.57	0.22	0.49	0.61	0.61	0.61	0.45	0.61	0.38	20.03
23	0.19	0.19	-	0.36	0.36	0.36	0.60	0.36	0.25	0.36	0.36	0.36	0.34	0.25	0.25	0.25	0.19	0.25	0.25	0.19	10.92
24	0.52	0.52	0.40	-	0.76	0.73	0.64	0.59	0.42	0.57	0.73	0.63	0.63	0.59	0.59	0.52	0.52	0.42	0.59	0.38	21.14
25	0.16	0.16	0.36	0.00	-	0.16	0.60	0.52	0.00	0.11	0.27	0.16	0.16	0.16	0.52	0.16	0.52	0.36	0.16	0.02	9.57
26	0.52	0.16	0.36	0.02	0.55	-	0.60	0.45	0.36	0.11	0.27	0.52	0.16	0.52	0.59	0.16	0.52	0.36	0.16	0.02	15.43
27	0.19	0.19	0.36	0.36	0.36	0.36	-	0.25	0.25	0.36	0.36	0.25	0.34	0.25	0.61	0.19	0.54	0.61	0.25	0.02	10.88
28	0.20	0.20	0.40	0.17	0.24	0.31	0.75	-	0.00	0.15	0.31	0.31	0.31	0.20	0.59	0.16	0.52	0.36	0.16	0.02	10.62
29	0.58	0.23	0.40	0.33	0.76	0.40	0.75	0.72	-	0.24	0.40	0.76	0.31	0.65	0.61	0.19	0.54	0.45	0.19	0.02	17.95
30	0.54	0.19	0.36	0.19	0.61	0.61	0.60	0.61	0.36	-	0.52	0.54	0.16	0.54	0.61	0.19	0.54	0.38	0.19	0.02	17.37
31	0.38	0.02	0.36	0.02	0.45	0.45	0.60	0.45	0.36	0.09	-	0.38	0.00	0.38	0.61	0.19	0.38	0.38	0.02	0.02	14.19
32	0.38	0.19	0.36	0.13	0.55	0.20	0.60	0.45	0.00	0.17	0.34	-	0.27	0.54	0.61	0.19	0.54	0.45	0.19	0.02	13.75
33	0.38	0.54	0.38	0.13	0.55	0.55	0.62	0.45	0.45	0.55	0.72	0.45	-	0.61	0.61	0.54	0.54	0.45	0.54	0.38	19.80
34	0.36	0.16	0.40	0.17	0.60	0.24	0.75	0.55	0.00	0.22	0.38	0.22	0.15	-	0.61	0.19	0.54	0.45	0.19	0.02	13.20
35	0.04	0.04	0.40	0.17	0.24	0.17	0.39	0.13	0.00	0.15	0.15	0.15	0.15	0.04	-	0.02	0.36	0.38	0.02	0.02	5.44
36	0.40	0.04	0.40	0.24	0.60	0.60	0.82	0.60	0.47	0.57	0.57	0.57	0.22	0.47	0.63	-	0.36	0.45	0.45	0.07	17.47
37	0.04	0.04	0.47	0.24	0.24	0.24	0.46	0.24	0.11	0.22	0.38	0.22	0.22	0.11	0.30	0.30	-	0.14	0.09	0.07	8.45
38	0.20	0.20	0.40	0.33	0.40	0.40	0.39	0.40	0.20	0.38	0.38	0.31	0.31	0.20	0.27	0.20	0.52	-	0.16	0.07	11.03
39	0.40	0.04	0.40	0.17	0.60	0.60	0.75	0.60	0.47	0.57	0.73	0.57	0.22	0.47	0.63	0.20	0.56	0.49	-	0.07	18.13
40	0.56	0.20	0.47	0.38	0.73	0.73	0.98	0.73	0.63	0.73	0.73	0.73	0.38	0.63	0.63	0.59	0.59	0.59	0.59	-	22.27
Φ^{-}	13.58	7.46	16.61	9.89	21.08	15.29	27.71	19.89	9.21	13.08	16.42	16.86	10.92	14.63	21.87	10.36	19.38	16.80	9.70	5.22	

6.3. Control of uncertainty: stochastic *PROMETHEE-2*

There are several problems associated with implementing the MultiCriteria Decision-Making methods in Geographical Information Systems (Zhou and Civco, 1996). First, it is well known that the input data to the Geographical Information System multicriteria evaluation procedures usually present the property of inaccuracy, imprecision, and ambiguity. In spite of this knowledge, the methods typically assume that the input data are precise and accurate. Some efforts have been made to deal with this problem by combining the Geographical Information System multicriteria procedures with sensitivity analysis (Lodwick *et al*., 1990) and error propagation analysis (Hevelink *et al*., 1989) Another approach is to use fuzzy logic methods (Malczewski, 2004).

According to Marinoni (2005) “it is often hard to choose the input values for the *PROMETHEE* procedure, since the criteria values usually do not have a single realization, but can obtain a range of possible values. Performing a *PROMETHEE* with the mean values produces some kind of mean result, but the uncertainty in either the input values or the result cannot be quantified. A solution to this dead-end is a stochastic approach, which utilizes probability distributions for the input parameters instead of single values. Such an approach uses the whole range of possible criteria value outcomes and extreme events are –according to their low outcome probabilities– realistically represented as rare events”.

As mentioned in chapter 2.3.4., the stochastic *PROMETHEE* approach first requires the assignment of theoretical distribution types to every criterion of the available alternatives. These distributions were assigned with the use of @Risk, which operates with common spreadsheet programs as Excell. Thus, the values of all the alternatives (polygons) for every criterion (raster layers) had to be exported in order to be imported into @Risk. For the creation of the database of the criteria values for every alternative, ERDAS 8.7 has been used. It was necessary to import the grids (criteria layers) into a same Layer stack, in order not to loose the spatial reference. The Layer stacks from every alternative were afterwards exported to ASCII files which, in turn, are easy to import into Excell.

The data for all alternatives and criteria were exhaustively analysed. The distribution types for every criteria and alternative to be used in the different land-use analysis were assigned with the help of the available distribution fitting tests, *K-S-Test* and *chi^2-test* for continuous variables, and *Anderson-Darling test* for categorical ones. Afterwards, *Monte Carlo simulation*, also integrated in @Risk, was applied to these distribution types to assign empirical populations. In our case the population number used was 5000, which covers the suggestion made by Palisade (2002) of more than 500 iterations for accurate results.

According to Marinoni (2005), starting a *Monte Carlo simulation* with *n* iterations for the specified distributions produces *n* realizations for every cell of the input matrix. Figure 69 shows the principle of one iteration cycle.

With the iteration cycles, 5000 preference matrices can be established which are then used to perform a *PROMETHEE-2* 5000 times. The results may then be used to establish a rank distribution for a specific alternative or a distribution of alternatives for a specific rank (Figure 70).

But, according to Marinoni (2005), the alternative possessing the highest number of first ranks may not necessarily be the best. Therefore, he suggested to calculate a dimensionless mean stochastic rank MSR for every alternative.

$$\mathrm{MSR}_{\mathrm{Aj,m}} = \frac{1}{n}\sum_{i=1}^{n}(R_i \cdot i) \quad \forall \mathrm{j} = 1, \ \ldots, \ \mathrm{n} \tag{8}$$

where:
m: number of iterations
Aj: j^{th} alternative
n: number of available alternatives
Ri: rank count for the i^{th} rank

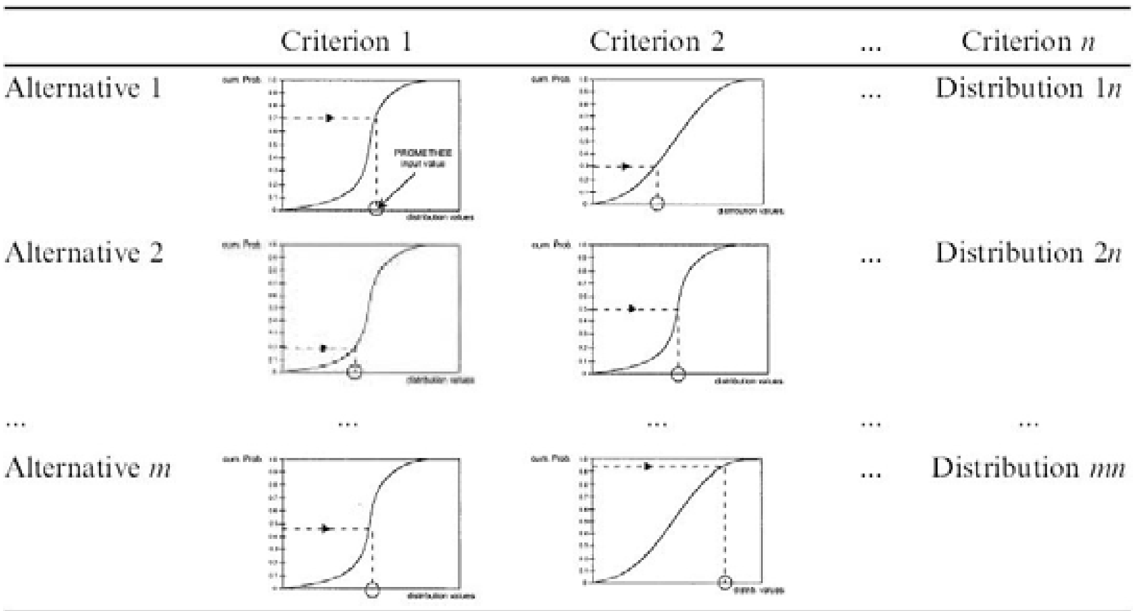


Figure 69: *PROMETHEE* input value determination for one iteration cycle. Source: Marinoni (2005).

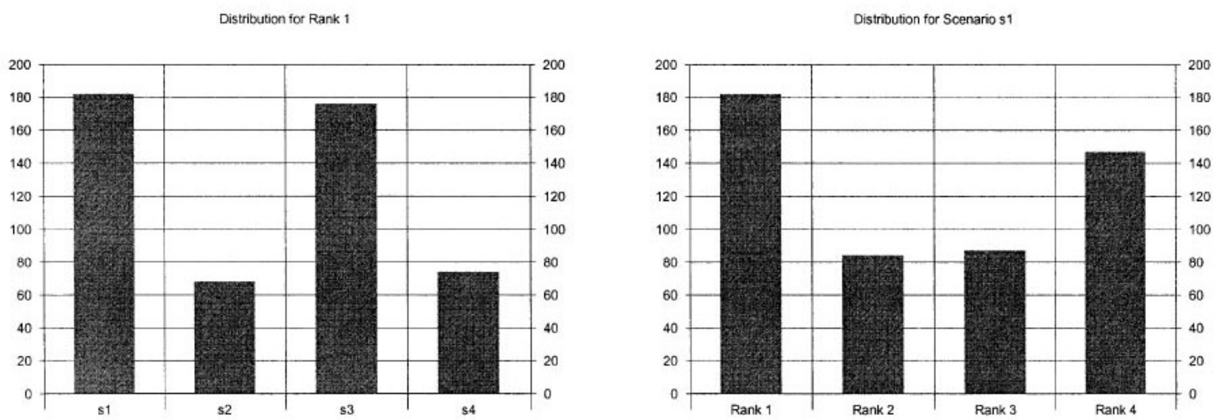


Figure 70: Left: distribution of 4 scenarios (s1,..., s4) for rank 1. Right: rank distribution for scenario 1. Source: Marinoni (2005).

According to Marinoni (2005), in order to compare mean stochastic ranks of simulations with different iteration counts, the MSR value must be standardised which leads to the stochastic rank index SI:

$$\mathrm{SI}_{\mathrm{Aj,m}} = \frac{MSR_{Aj,m} - MSR_{\min,m}}{MSR_{\max,m} - MSR_{\min,m}} \qquad (9)$$

where:
m: number of iterations
SI_{Aj}: stochastic rank index for the jth alternative
MSR_{Aj}: MSR for the j^{th} alternative
MSR_{min}: the lowest possible *MSR* value
MSR_{max}: the largest possible *MSR* value

The more the *SI* value approaches 0, the better the alternative.

6.3.1. Distribution types

It should be noted that, due to local/regional variability, the alternative dependant distributions of a criterion usually display different mean values or standard deviations. Thus, although it seems reasonable, at first sight, to determine one distribution type for one criterion, if location dependant statistical analyses indicate varying distribution types, then varying types should be assigned to one criterion. Distribution types had to be assigned to every alternative and criterion in the four different site selection analyses. Therefore, a total of 696 distributions were analysed and defined.

In our case, in many criteria, it was necessary to apply different distribution types to the alternatives due to the variety of distributions resulting from the statistical analysis. The following chapter describes the most significant examples.

Table 60, 61, 62 and 63 show the distribution types assigned to every alternative and criterion for the four different suitability analyses. As mentioned in chapter 6.3, the distribution types were assigned with the help of the distribution fitting tests available in @Risk. Anderson-Darling test was used for categorical criteria and chi^2-test for continuous ones.

In the case of continuous criteria, in many cases, both distribution fitting tests, Anderson-Darling and chi^2-test, gave the same best distribution type, thus implying its selection. However, in cases where both tests presented different results, the most common distribution type in the remaining alternatives was selected.

In addition, all the distribution models were selected to have physical sense. This is exemplified by the overburden thickness criteria in alternative 1 in the sand and gravel extraction suitability analysis (Figure 89). In this case, a lognormal distribution was selected by the fitting test, but exponential distribution was chosen in order to avoid the presence of negative values in overburden thickness, which are not present in the real world.

The more commonly used distributions for continuous variables (groundwater depth, distance to roads, nuclei and natural areas, elevation above sea level, slope percentage, etc.) are normal and lognormal, but also logistic and exponential distributions are present in some variables, *i.e.* overburden thickness, groundwater protection and/or doline susceptibility.

A binomial distribution was selected for categorical variables with two categories as the constraints. On the other hand, in categorical variables with more than two classes, assigning a categorical distribution implies the introduction of categories not present in the alternative. For example, if one alternative presented values 1 and 4 in agricultural capability criterion, the distribution selected by the fitting test would have given values 2 and 3 to this alternative, which are not present in the real world. Thus, instead of assigning a distribution, the percentage of cases in every category was calculated. This was also the case for some continuous variables, which presented few different values, thus complicating the distribution selection (*i.e.* alternative 12 in groundwater depth criterion, Table 60). In these cases, the percentage of every value was also introduced in the analysis.

When an alternative resulted in strange distributions because of its is partially located outside the areas of some models, the solution was to apply a distribution only to the values inside the model, and to keep the percentage of values outside the model (cases in bold letters in tables 60, 61, 62 and 63).

Also some difficulties were experienced in the case of the doline susceptibility criterion, where some alternatives presented continuous values near to value 0. The reasons for this strange distribution of these values were discovered by analysing the data (Figure 96 and 100). Since it was not possible to apply the percentage of values in these cases, a decision was made to apply a exponential distribution in order to avoid the introduction of negative values in the suitability analysis, even though the adopted solution was not absolutely satisfactory. Finally, some alternatives presented the same value for the whole alternative (unique value in the tables).

Some representative examples of the selected distribution types can be seen in Figure 71 to 108. The blue bars represent the original values of the alternative and the red line the distribution applied to these values.

Table 60: Distribution types for every alternative and criterion for sand and gravel extraction sites suitability analysis.

Alterna.	Distance to extractions	Groundwater depth	Groundwater protection	Distance to nucleus	Distance to natural areas	Distance to roads	Resource thickness	Irrigation capacity of soil	Overburden thickness	Constraints
1	Lognormal	Lognormal	Unique value	Normal	Normal	Lognormal	Normal	Unique value	Exponential	Binomial
2	Lognormal	Normal	Unique value	Lognormal	Lognormal	Normal	Logistic	Unique value	Exponential	Unique value
3	Normal	Lognormal	Unique value	Normal	Normal	Normal	Normal	Unique value	Normal	Unique value
4	Normal	Logistic	Logistic	Normal	Lognormal	Lognormal	Normal	Unique value	Exponential	Unique value
5	Normal	Normal	**Normal**	Normal	Lognormal	Normal	Normal	Unique value	Exponential	Binomial
6	Normal	Percentage	Logistic	Normal	Normal	Normal	Normal	Unique value	Normal	Unique value
7	Normal	Normal	Logistic	Normal	Normal	Normal	Normal	Unique value	Unique value	Unique value
8	Normal	Normal	Logistic	Lognormal	Lognormal	Lognormal	Logistic	Unique value	Normal	Unique value
9	Lognormal	Unique value	Unique value	Lognormal	Normal	Normal	Unique value	Unique value	Unique value	Unique value
10	Normal	Logistic	Percentage	Lognormal	Normal	Normal	Lognormal	Percentage	Exponential	Unique value
11	Lognormal	Exponential	Logistic	Normal	Normal	Normal	Logistic	Unique value	Normal	Unique value
12	Normal	Percentage	Logistic	Normal	Exponential	Normal	Logistic	Unique value	Normal	Unique value

Table 61: Distribution types for every alternative and criterion for irrigated areas suitability analysis.

Alternat.	Elevation above sea level	Change in erosion	Groundwater protection	Location of natural areas	Slope percentage	Irrigation capability of soils	Dolines susceptibility	Constraints
1	Normal	Percentage	Unique value	Percentage	Lognormal	Percentage	Unique value	Binomial
2	Normal	Percentage	Unique value	Percentage	Lognormal	Percentage	Unique value	Binomial
3	Lognormal	Percentage	Percentage	Percentage	Lognormal	Percentage	Unique value	Unique value
4	Lognormal	Unique value	Percentage	Percentage	Lognormal	Percentage	Unique value	Binomial
5	Lognormal	Unique value	Lognormal	Percentage	Lognormal	Percentage	Exponential	Binomial
6	Normal	Unique value	Unique value	Unique value	Lognormal	Percentage	Exponential	Binomial
7	Lognormal	Percentage	Percentage	Percentage	Lognormal	Percentage	Unique value	Binomial
8	Lognormal	Unique value	Percentage	Percentage	Lognormal	Percentage	Unique value	Binomial
9	Lognormal	Unique value	Lognormal	Unique value	Lognormal	Percentage	Exponential	Binomial
10	Lognormal	Unique value	Lognormal	Percentage	Lognormal	Percentage	Exponential	Binomial

Table 62: Distribution types for every alternative and criterion for industrial settlements suitability analysis.

Alterna.	Groundwater protection	Dolines susceptibility	Flooding hazard	Location of natural areas	Agricultural capability of soils	Slope percentage	Geotechnical characteristics	Constraints
1	Percentage	Lognormal	Percentage	Percentage	Percentage	Lognormal	Unique value	Binomial
2	Logistic	Normal	Percentage	Percentage	Percentage	Lognormal	Unique value	Binomial
3	Exponential	Percentage	Unique value	Unique value	Unique value	Normal	Unique value	Binomial
4	Logistic	Normal	Unique value	Percentage	Percentage	Lognormal	Percentage	Binomial
5	Logistic	Lognormal	Percentage	Unique value	Unique value	Lognormal	Unique value	Binomial
6	Logistic	Lognormal	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
7	Unique value	Unique value	Unique value	Percentage	IntUniform	Lognormal	Percentage	Binomial
8	Logistic	Exponential	Unique value	Unique value	Unique value	Lognormal	Unique value	Binomial
9	Percentage	Exponential	Unique value	Unique value	Unique value	Lognormal	Unique value	Binomial
10	Logistic	Exponential	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
11	Exponential	Unique value	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
12	Logistic	Percentage	Unique value	Percentage	Unique value	Logistic	Unique value	Binomial
13	Percentage	Exponential	Unique value	Unique value	Percentage	Normal	Unique value	Binomial
14	Percentage	Unique value	Unique value	Percentage	Percentage	Lognormal	Percentage	Binomial
15	Percentage	Lognormal	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
16	Exponential	Percentage	Unique value	Unique value	Unique value	Lognormal	Percentage	Unique value
17	Logistic	Normal	Unique value	Unique value	Unique value	Lognormal	Percentage	Binomial
18	Logistic	Lognormal	Unique value	Percentage	Percentage	Exponential	Percentage	Binomial
19	Logistic	Exponential	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
20	Logistic	Lognormal	Unique value	Unique value	Unique value	Normal	Percentage	Binomial
21	Percentage	Exponential	Unique value	Unique value	Percentage	Normal	Unique value	Binomial
22	Logistic	Normal	Unique value	Unique value	Percentage	Normal	Unique value	Binomial
23	Percentage	Percentage	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
24	Percentage	Percentage	Unique value	Unique value	Unique value	Normal	Unique value	Unique value
25	Unique value	Unique value	Unique value	Percentage	Percentage	Normal	Unique value	Unique value
26	Unique value	Unique value	Unique value	Percentage	Percentage	Lognormal	Percentage	Binomial
27	Percentage	Exponential	Unique value	Percentage	Percentage	Lognormal	Percentage	Binomial

Table 63: Distribution types for every alternative and criterion for urban areas suitability analysis.

Alterna.	Dolines susceptibility	Flooding hazard	Location of natural areas	Agricultural capability of soils	Slope percentage	Geotechnical characteristics	Constraints
1	Normal	Unique value	Unique value	Percentage	Logistic	Unique value	Binomial
2	Lognormal	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
3	Lognormal	Unique value	Unique value	Unique value	Lognormal	Unique value	Binomial
4	Normal	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
5	Exponential	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
6	Normal	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
7	Exponential	Unique value	Unique value	Percentage	Logistic	Unique value	Binomial
8	Normal	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
9	Exponential	Unique value	Unique value	Unique value	Lognormal	Unique value	Binomial
10	Exponential	Unique value	Unique value	Unique value	Lognormal	Percentage	Binomial
11	Exponential	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
12	Unique value	Unique value	Percentage	Percentage	Lognormal	Percentage	Binomial
13	Percentage	Unique value	Percentage	Percentage	Lognormal	Percentage	Binomial
14	Unique value	Unique value	Percentage	Percentage	Exponential	Percentage	Binomial
15	Unique value	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
16	**Exponential**	Unique value	Percentage	Percentage	Exponential	Percentage	Binomial
17	Unique value	Unique value	Percentage	Percentage	Lognormal	Percentage	Binomial
18	Lognormal	Unique value	Unique value	Unique value	Lognormal	Percentage	Binomial
19	Lognormal	Unique value	Unique value	Percentage	Logistic	Unique value	Binomial
20	Normal	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
21	Percentage	Unique value	Unique value	Unique value	Lognormal	Percentage	Binomial
22	Exponential	Unique value	Percentage	Unique value	Lognormal	Percentage	Binomial
23	Unique value	Unique value	Unique value	Percentage	Lognormal	Unique value	Unique value
24	Normal	Percentage	Unique value	Percentage	Lognormal	Percentage	Binomial
25	Normal	Percentage	Unique value	Unique value	Lognormal	Unique value	Binomial
26	Normal	Percentage	Unique value	Percentage	Lognormal	Unique value	Binomial
27	Exponential	Unique value	Percentage	Percentage	Lognormal	Unique value	Binomial
28	Exponential	Percentage	Unique value	Percentage	Logistic	Unique value	Binomial
29	Unique value	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
30	Unique value	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
31	Exponential	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
32	Normal	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
33	Normal	Percentage	Unique value	Percentage	Exponential	Unique value	Binomial
34	Logistic	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
35	Lognormal	Unique value	Unique value	Percentage	Lognormal	Unique value	Binomial
36	Exponential	Unique value	Unique value	Unique value	Lognormal	Percentage	Binomial
37	Percentage	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
38	Percentage	Unique value	Unique value	Percentage	Lognormal	Percentage	Binomial
39	Percentage	Unique value	Percentage	Percentage	Lognormal	Unique value	Binomial
40	Exponential	Unique value	Unique value	Unique value	Lognormal	Percentage	Binomial

Figure 71: Distribution assigned to distance to old extractions in alternative 1 (sand and gravel extraction site).

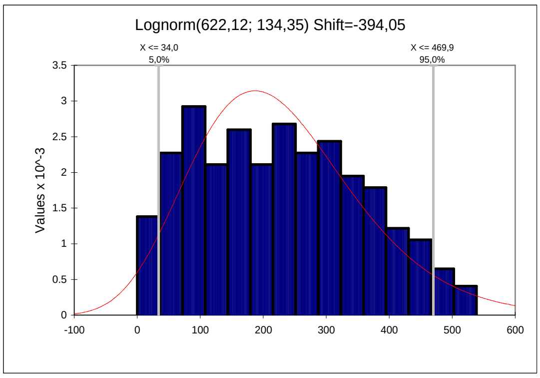


Figure 72: Distribution assigned to distance to old extractions in alternative 3 (sand and gravel extraction site).

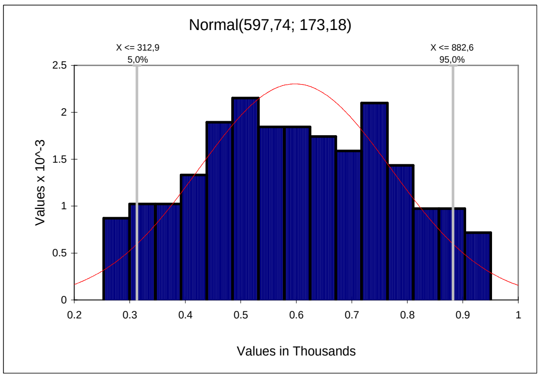


Figure 73: Distribution assigned to groundwater depth in alternative 2 (sand and gravel extraction site).

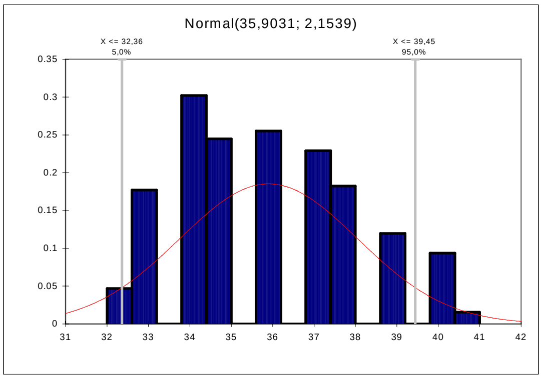


Figure 74: Distribution assigned to groundwater depth in alternative 3 (sand and gravel extraction site).

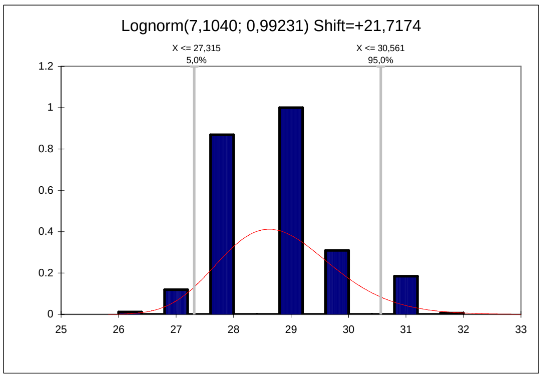


Figure 75: Distribution assigned to groundwater depth in alternative 10 (sand and gravel extraction site).

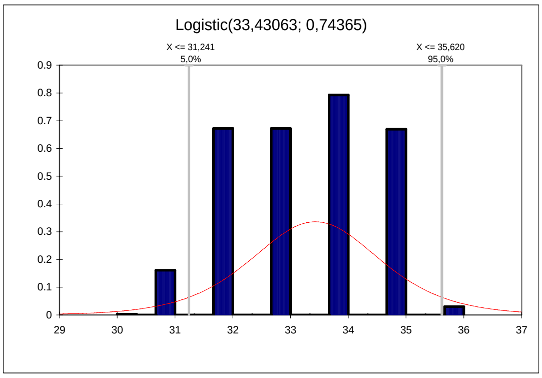


Figure 76: Distribution assigned to groundwater depth in alternative 11 (sand and gravel extraction site).

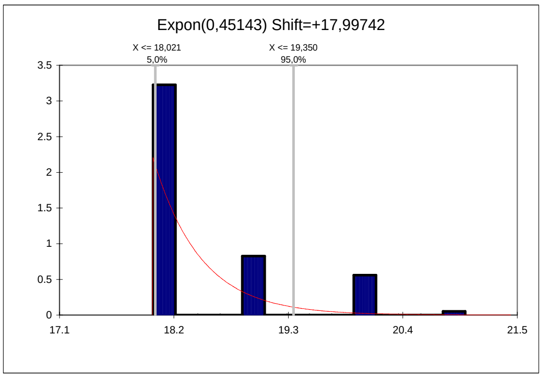


Figure 77: Distribution assigned to groundwater protection in alternative 4 (sand and gravel extraction site).

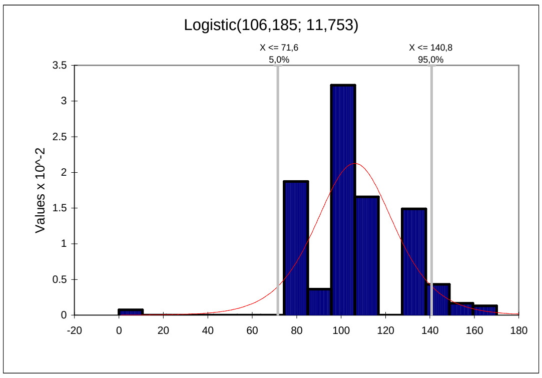


Figure 78: Distribution assigned to groundwater protection in alternative 5 (sand and gravel extraction site).

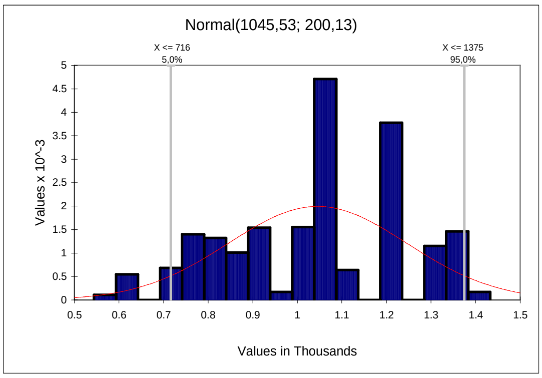


Figure 79: Distribution assigned to distance to urban nuclei in alternative 1 (sand and gravel extraction site).

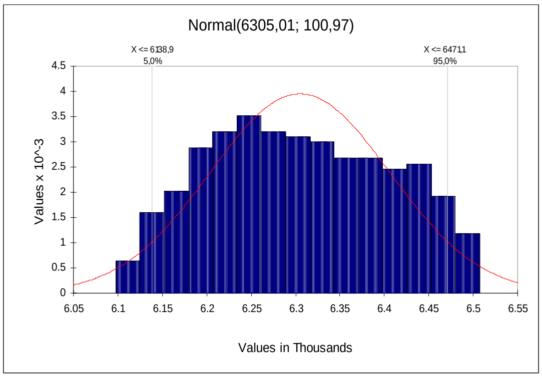


Figure 80: Distribution assigned to distance to urban nuclei in alternative 2 (sand and gravel extraction site).

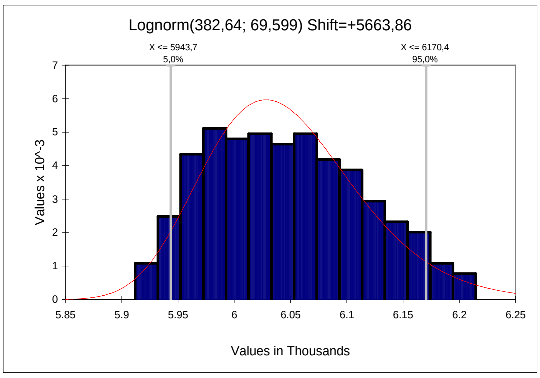


Figure 81: Distribution assigned to distance to natural areas in alternative 1 (sand and gravel extraction site).

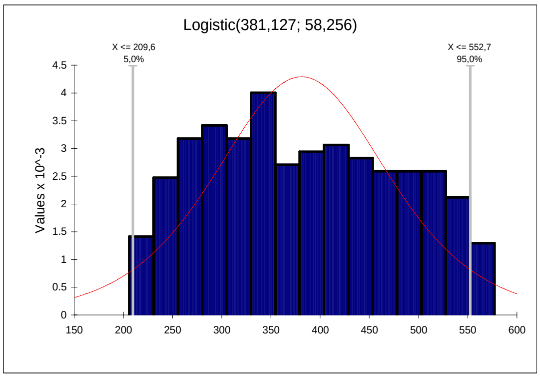


Figure 82: Distribution assigned to distance to natural areas in alternative 2 (sand and gravel extraction site).

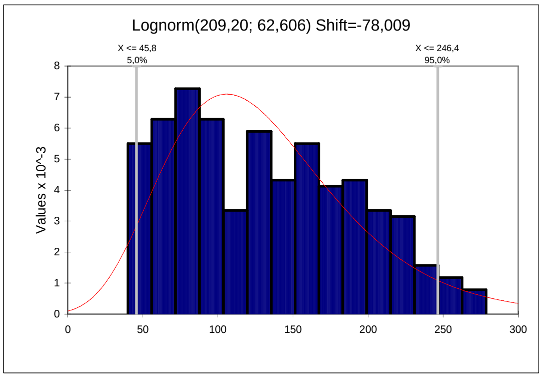


Figure 83: Distribution assigned to distance to natural areas in alternative 12 (sand and gravel extraction site).

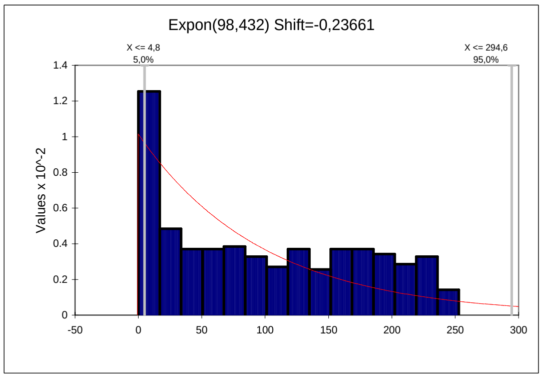


Figure 84: Distribution assigned to distance to roads in alternative 1 (sand and gravel extraction site).

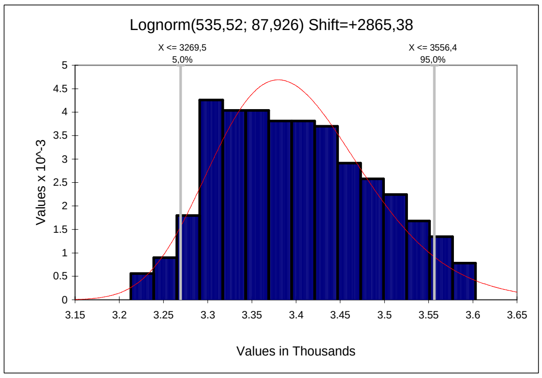


Figure 85: Distribution assigned to distance to roads in alternative 2 (sand and gravel extraction site).

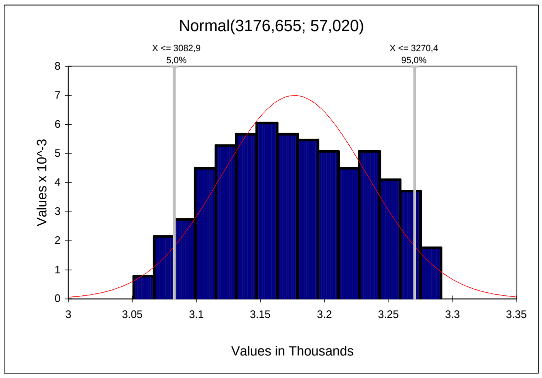


Figure 86: Distribution assigned to resource thickness in alternative 2 (sand and gravel extraction site).

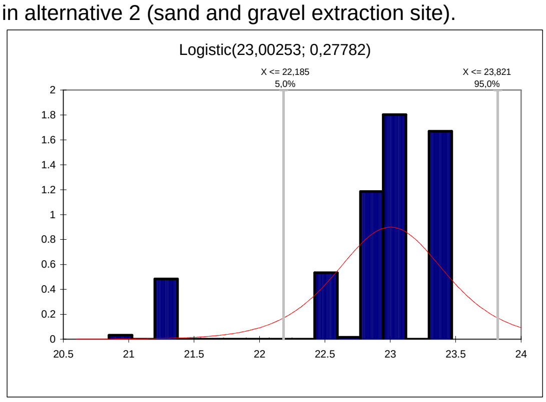


Figure 87: Distribution assigned to resource thickness in alternative 4 (sand and gravel extraction site).

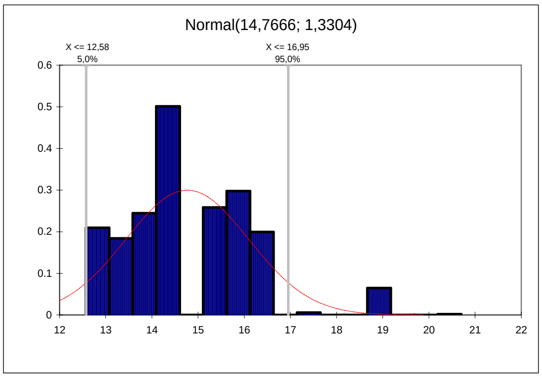


Figure 88: Distribution assigned to resource thickness in alternative 10 (sand and gravel extraction site).

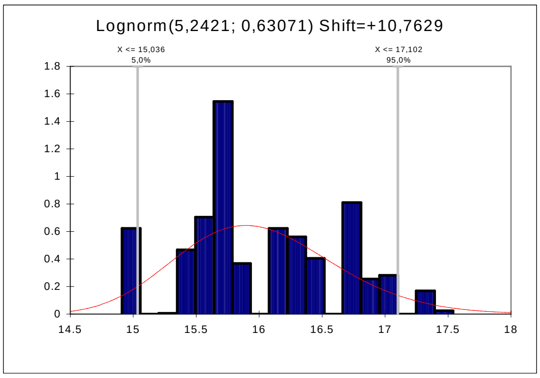


Figure 89: Distribution assigned to overburden thickness in alternative1 (sand and gravel extraction site).

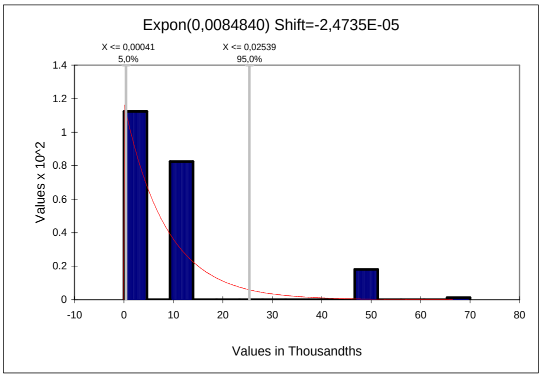


Figure 90: Distribution assigned to overburden thickness in alternative 3 (sand and gravel extraction site).

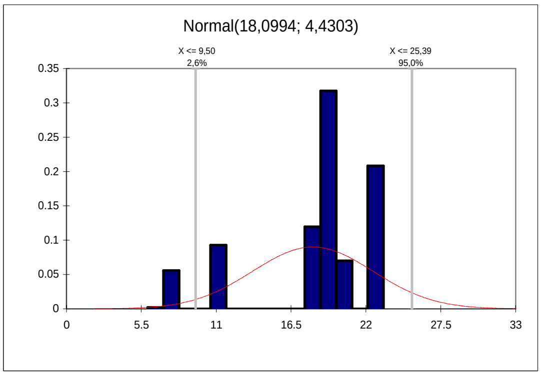


Figure 91: Distribution assigned to the constraints in alternative 1 (sand and gravel extraction site).

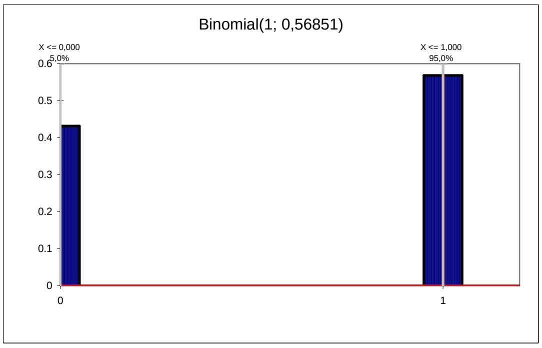


Figure 92: Distribution assigned to elevation above sea level in alternative 1 (irrigation areas).

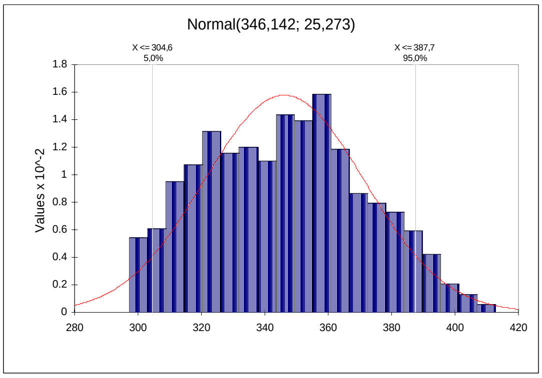


Figure 93: Distribution assigned to elevation above sea level in alternative 3 (irrigation areas).

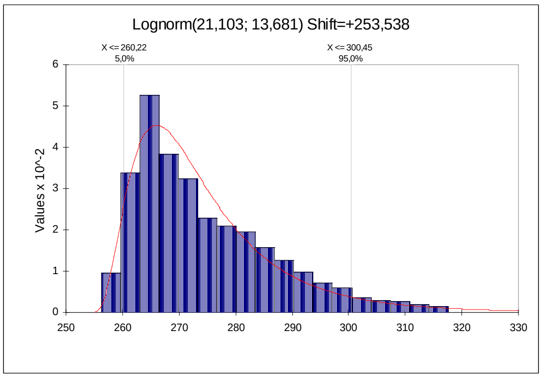


Figure 94: Distribution assigned to groundwater protection in alternative 5 (irrigation areas).

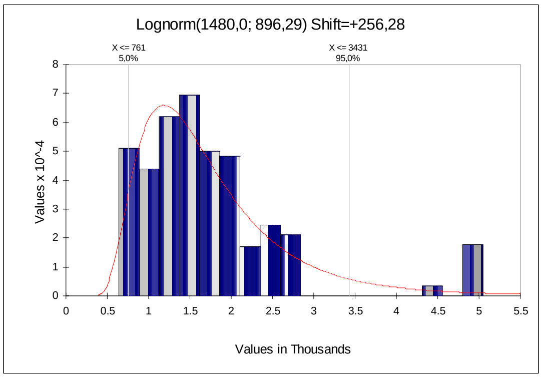


Figure 95: Distribution assigned to slope percentage in alternative 1 (irrigation areas).

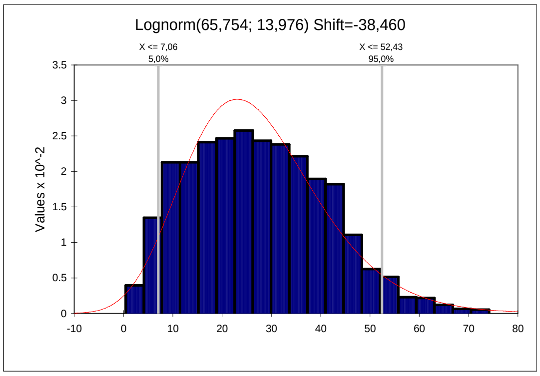


Figure 96: Distribution assigned to doline susceptibility in alternative 6 (irrigation areas).

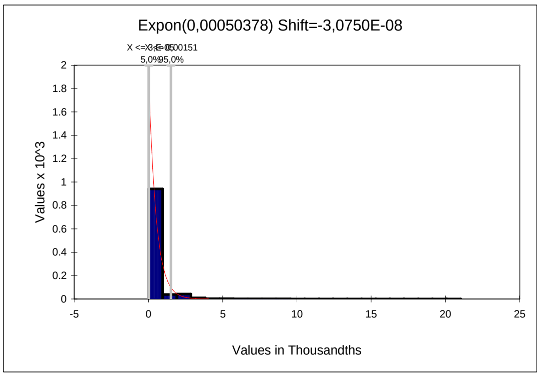


Figure 97: Distribution assigned to groundwater protection in alternative 3 (industrial settlements).

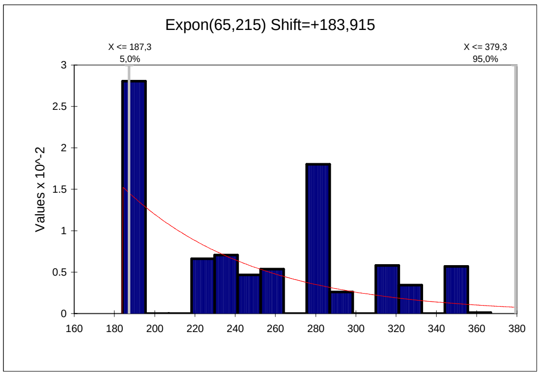


Figure 98: Distribution assigned to groundwater protection in alternative 2 (industrial settlements).

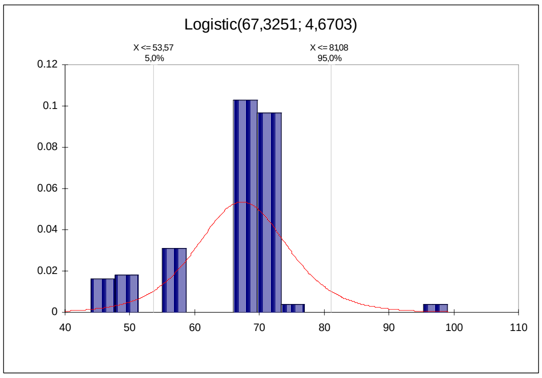


Figure 99: Distribution assigned to doline susceptibility in alternative 5 (industrial settlements).

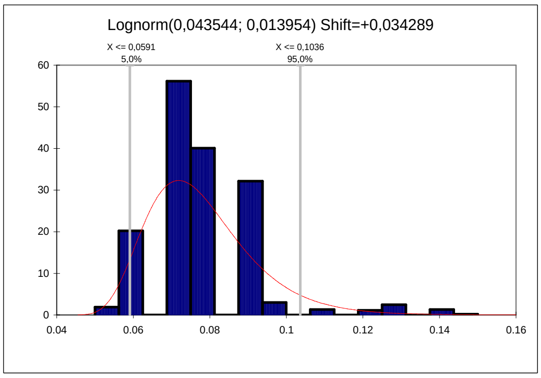


Figure 100: Distribution assigned to doline susceptibility in alternative 8 (industrial settlements).

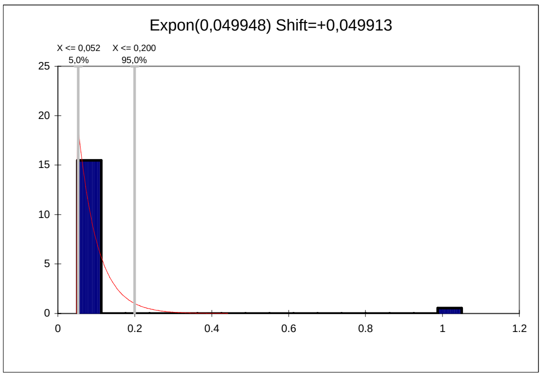


Figure 101: Distribution assigned to doline susceptibility in alternative 2 (industrial settlements).

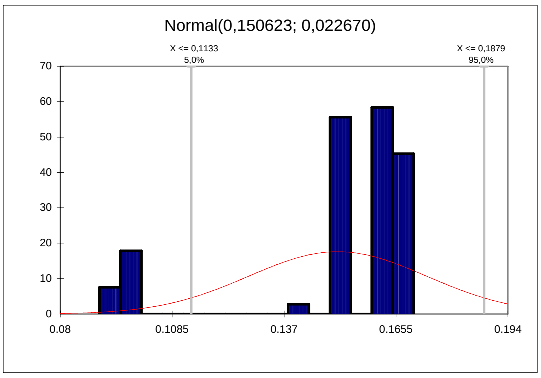


Figure 102: Distribution assigned to slope percentage in alternative 2 (industrial settlements).

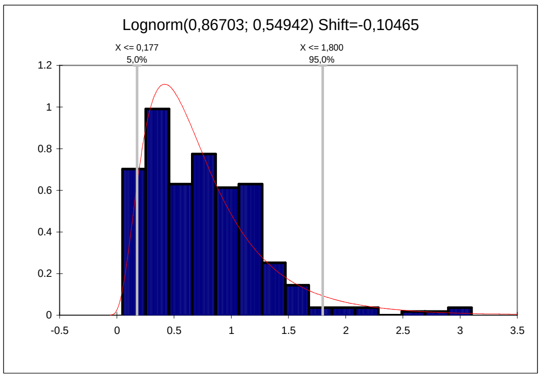


Figure 103: Distribution assigned to slope percentage in alternative 12 (industrial settlements).

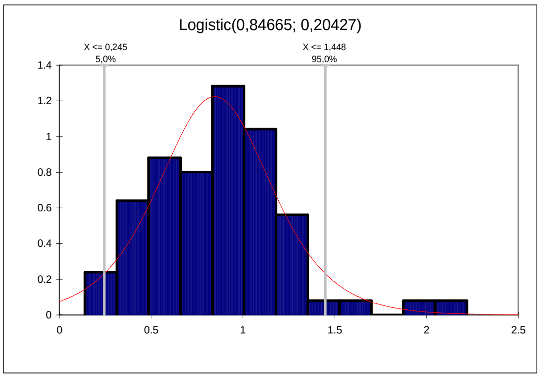


Figure 104: Distribution assigned to slope percentage in alternative 18 (industrial settlements).

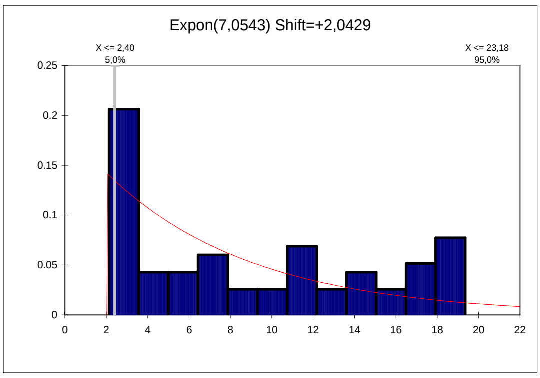


Figure 105: Distribution assigned to doline susceptibility in alternative 27 (urban development).

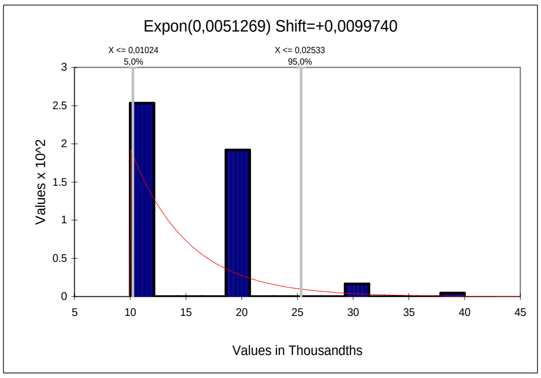


Figure 106: Distribution assigned to doline susceptibility in alternative 2 (urban development).

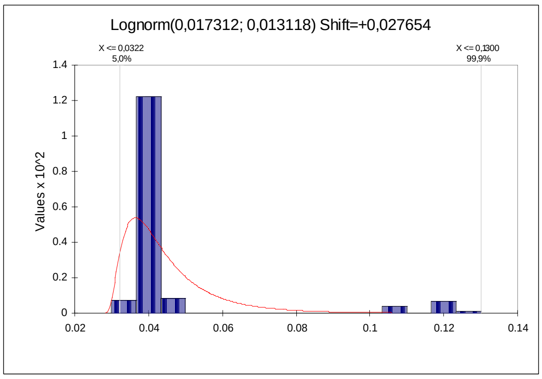


Figure 107: Distribution assigned to doline susceptibility in alternative 8 (urban development).

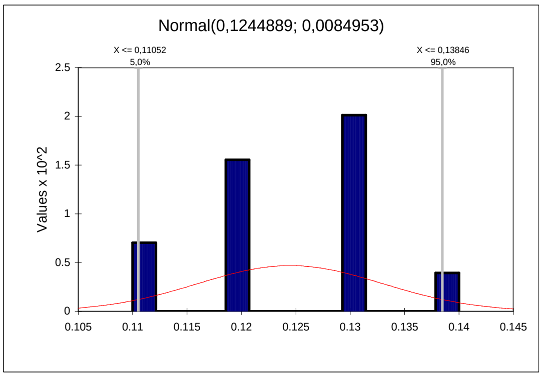
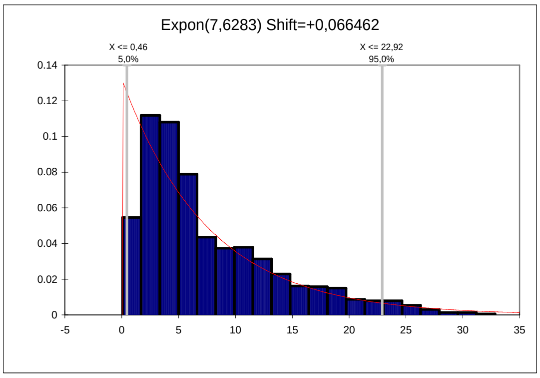


Figure 108: Distribution assigned to slope percentage in alternative 14 (urban development).



6.3.2. Results

The results of the site selection suitability analysis after applying stochastic *PROMETHEE-2* can be seen in maps 65, 66, 67and 68. In the extraction site selection suitability analysis, alternative 10, a real alternative located in the contact between the old terraces and pediments near the airport, presents the first rank in both approaches. In fact, there are only a few changes between both the *PROMETHEE-2* and the stochastic *PROMETHEE-2* approaches. Alternatives with the third and fourth rank position (Map 65) change their ranking, so that, in the simple version, the most preferable is alternative 2, while, in the stochastic *PROMETHEE-2*, it is 1. This is because of the location of a small part of the latter in an area with use restrictions (constraints). As a consequence, this alternative is not preferable in *PROMETHEE-2*, as the mean value of constraint criterion is higher in alternative 1 than in 2. But, it is preferable in stochastic *PROMETHEE-2*, as the percentage of zeros (no constraints) in the criterion is higher than the percentage of ones (constraints), and the rest of criteria present higher suitability in alternative 1. Alternatives 5 and 9 present a similar situation, but, in this case, the criterion making the difference is overburden thickness.

In the irrigation areas, the same alternative, number 7, also obtains the first ranking in both approaches (Map 66). In general, the first and the last rankings match in *PROMETHEE-2* and stochastic *PROMETHEE-2.* However, there are some exceptions. For example, alternative 9 changes from ranking 2 to ranking 5, mainly due to the heterogeneity of its values, especially with regard to the groundwater protection criterion. This heterogeneity produces higher mean values when applying *PROMETHEE-2*, which implies a higher ranking in relation to the stochastic *PROMETHEE-2*. A similar situation is seen in alternative 10, where the application of the stochastic approach results in a reduced ranking.

The first rank is different for industrial settlement suitability analysis. However, there are few differences in the *SI* values and total flows between the first rankings: alternatives 7, 25, 23, 26 and 27 (Map 67). All these alternatives are located in the areas with higher suitability values in the site search analysis. The worst rankings, alternative 16, 17 and 18, are located inside restricted areas, but also in the proximity of *El Burgo de Ebro* village.

Finally, in urban development suitability analysis, the first rank also changes from alternative number 40 to alternative number 12 (Map 68). The possible reason for this result is the existence of a small area inside alternative 12, with low suitability values, which reduces the mean criteria value used in the *PROMETHEE-2*, and, as a consequence, its rank position. In contrast, these low suitability values present are insignificant in the stochastic approach, since they form the tail of the distribution. This is also the case of the last ranking position in *PROMETHEE-2*. When applying the stochastic version the rank position is increased considerably. In this case the causative factor is a small area located inside a restricted sector. Alternative 16 is another remarkable case because it shows an increase of 26 rank positions, also caused by the constraints. The alternatives that are lowered in rank in the stochastic approach, *i.e.* number 31 and 33, generally have homogeneous middle-good suitability values throughout, which results in a better positioning when applying the mean value in the simple *PROMETHEE-2*.

7. Conclusions

7.1. General methodology

The main objective of this project was to develop a methodology in order to assess, record and map geo-hazards and geo-resources 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. This would fulfil the demands and overall objective of Agenda 21, which aims to encourage as many countries as possible to undertake inventories of land resources and hazards. This is a prerequisite to establishing a land information system to improve or restructure the decision-making process with the objective of achieving a sustainable development, especially in still growing cities. In general terms, this workflow would imply:

- Data gathering of as much information as possible related to geology, geomorphology, soils, vegetation, land-use, etc.
- Development of a Geographical Information System with the collected information.
- Land evaluation and modelling with respect to geo-hazards and geo-resources, by using Geographical information Systems and three-dimensional geological modelling.
- Land-use suitability analysis by using Spatial Decision Support Systems.

The data gathering and development of the Geographical Information System are tedious and extremely important parts of the methodological workflow. The information characteristics and quality as well as the subsequent processing within the Geographical Information System 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 geo-hazards and geo-resources models.

The selection of the land evaluation methodologies should take into account several factors i.e. the availability and quality of information for the development, their adequacy to the study area and the final objective of the models. In the case of this workflow, this would be to be used as geoscientific criteria in a land-use suitability analysis.

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 adventages and disadventages. Thus, the selection between quantitative and qualitative approaches should be based on the factors mentioned above.

In addition, the introduction of three-dimensional information in the modelling process, especially in the models integrating geological information, should improve the quality of the results, as was demonstrated in the dolines susceptibility model and the groundwater vulnerability models (see chapters 5.2.3.2 and 5.3.5). Thus, three dimentional approaches should be integrated in the land evaluation process.

Spatial Decision Support Systems combine the capabilities of Geographical Information Systems and decision support tools in terms of multi-criteria evaluation methodologies. These tools provide a considerable aid in the effort of solving land-use conflicts that commonly appear in sustainable land-use management.

Multi-criteria evaluation methodologies have been criticized for their subjectivity. Nevertheless, it is important to realize that land-use decisions are made by managers who should finally decide between different uses. Thus, the land-use decision process is highly subjective. Multi-criteria evaluation methodologies have made a great effort in the attempt to introduce as much objectivity as possible in a subjective process. As a consequence, these are proper methodologies to support the land-use decision process.

7.2. Land evaluation analysis.

7.2.1. Sand and gravel deposits

As mentioned above, the development of a three-dimentional geological model of the study area was of great value in the geohazards and geo-resources modelling process, especially in the case of sand and gravel location, groundwater vulnerability and dolines susceptibility models.

In the case of the sand and gravel resources model, the development of the three-dimensional model was even more important, because of the three-dimensional characteristics of this resource. The collection of new data from different private enterprises was very important, since there were very few boreholes, which reached the Tertiary surface under the Quaternary in the IPA database from the Ebro River Authority. However, it is also important to stress the lack of borehole information downstream of Zaragoza and in the pediments sector upstream of Zaragoza, where the quality of the models is not as good as expected.

Nevertheless, this attempt to quantify the thickness of raw materials could be considered as a good step towards understanding the sand and gravel resources in the study area, in comparison with previous studies where a simple cartography of the terraces was presented (see chapter 2.3.3.4).

The maximum thickness of resource, more than 35 m, is located in terrace T5, situated immediately south-west of Zaragoza, in some sectors of T4 upstream of Zaragoza, often covered by glacis deposits, making its exploitation more difficult, and in the contact between the Jalón and Ebro Valleys. Very thick resources were located in the contact between Gállego and Ebro Valleys north-east of Zaragoza. Important deposits, more than 20 m thick, can be found surrounding these areas, and in the T6 level located upstream of Zaragoza.

Very thick sand and gravel deposits are also present in the pediments upstream of Zaragoza, where the oldest alluvial terrace levels are presumably covered by the glacis. Nevertheless, due to the lack of information in this sector, it is difficult to assess whether these terrace levels have been eroded, prior to pediment deposition, or still exist under these. Consequently, it is probable that the model provides unrealistcally large thickness in this sector.

7.2.2. Natural areas under protection or worth protecting

With regards to the landscape resources, almost all the natural areas of environmental and geoscientific value are protected by environmental law or land management planning, although, in some cases, this protection is not very strict with the exception of the *Natural Reserve of the Oxbows in La Alfranca, Pastriz, La Cartuja y El Burgo de Ebro,* which is properly protected. Also remarkable is the initiative by the Aragon Government, who recently created an inventory of wetlands. The main objective of this exercise is the maintenance and conservation of these areas in the Aragon Region, as a response to a observed loss of these areas by 60% due to anthropic factors. However, few areas in our study were included in this inventory. It is our opinion however, that these areas should also be protected in view of their environmental value. They harbor a highly diverse flora and fauna and also function as a refuge for many bird species. As a result the mapping of wetlands was carried out beyond the loimits of the study area.

The areas, yet without protection, are mostly located in the Ebro River upstream of Zaragoza and along the *Huerva, Jalón* and *Gállego* Rivers. Some of these areas correspond to salty wetlands, whose extension has extremely diminished in the last decades, especially in the surroundings of *Casetas*. Thus, the still remaining areas (*Ojos del Cura, Ojo del Fraile, Torre del Chocolatero* and *Ojos de Matamala*) should be protected.

In addition to this, two sectors covered by natural and reforested *Pinus halepensis* forest in the *La Muela* structural platform slopes and *Montes de Torrero* area were also mapped. These areas represent the vegetation level of *Pinus halepensis* and *Quercus coccifera*, which are both relatively rare in the study area. Additionally these areas are representative of the scarce forest areas in the study area, with the exception of the river banks.

In general, it is our opinion that all the mapped areas should be protected, in the absence legal protection, and more attention should be paid to comply with the law, in the protected areas.

7.2.3. Agricultural capability of the soils

The Cervatana model (C.S.I.C., 1996; de la Rosa *et al.*, 2002, 2004) was successfully applied in relation to the agricultural capability of soil (see chapter 4.3). In this model, the prediction of general land-use capability is the result of a qualitative evaluation process or overall interpretation of the following biophysical factors: relief, soil, climate, and current use or vegetation. Actual models tend to be more crop oriented, because of the final objective of these maps (land-use suitability analysis). However the model was used in this study because it has been developed with Mediterranean information and had already been applied with success in the surroundings of the study area at a lower scale.

The map unit used by this model is the unique-condition unit or homogeneous unit. One of the main factors determining the agricultural capability is the soil. The lack of a good cartography of soils at the work scale in the study area determined the development of a morpho-edaphic units cartography based on the division of the terrain in homogeneous units.

Therefore, a homogeneous unit mapping was performed using geomorphology as the main criteria for the division, following the suggestions of Amadio *et al*. (2002). Land cover, which combines the climatic and vegetation conditions, was also used as a secondary criterion. A total of fourteen homogeneous units were distinguished.

Taking into account all the aforementioned aspects and the fact that this model was developed for mediterranean regions the Cervataba model was selected for modelling the agricultural capability of the soils (see chapters 2.3.3.4 and 4.3).

Most of the study area shows moderate general agricultural capability. The main limiting factor is the climate, due to the aridity of the study area. The degraded reliefs in Tertiary gypsums, used for arable land, are also classified as moderately capable. However, in this case soil and climate are the limiting factors. This may be explained by the reduced useful depth of the soil. The degraded reliefs in Tertiary sediments with sclerophyllous vegetation are also classified as moderately capable and slope is the new limiting factor. Finally, the endorheic areas are classified as marginally capable for agricultural, because of the salinity of the soils.

The irrigation capability approach was developed for the irrigation use suitability analysis. Here, the highest irrigation capability appears in the flood plain with calcaric fluvisols, which have a good capability. The only limiting factor in this case is carbonate content. Petric calcisols and calcaric cambisols, mainly located in terraces and pediments, also have good irrigation capability, but with stoniness and carbonate content as limiting factors. Calcisols have drainage as third factor, while cambisols, the gypsum content. The degraded reliefs with regosols and flat bottom valleys with gypsisols have a moderate capability due to the gypsum content. And finally, solonchacks show marginal irrigation capability, due to their electrical conductivity.

As mentioned above, the importance of some soil properties, which are indispensable for determining agricultural capability, erosion susceptibility and groundwater vulnerability, in addition to the lack of a detailed soil map of the study area, made the creation of a morpho-edaphic unit map necessary. The formation of the soil depends on several landscape factors: climate, parent material, vegetal cover, slope, etc. Thus, the establishment of different landscape units with homogeneous landscape factors allows the creation of a morpho-edaphic or geo-edaphic units map by assigning a type of soil to every landscape unit.

However, to improve the results of our investigation and many other future studies which will require soil information, i.e. 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 many places where this information is limited and very important in the land-use management, as the soil is the supporter of all land uses.

7.2.4. Erosion susceptibility

A qualitative weighing method developed by van Zuidam and van Zuidam-Cancelado (1979) was used in the erosion susceptibility modelling. The map unit used in this method is also the unique condition or homogeneous unit. Thus, the homogeneous unit map developed for the agricultural capability of the soil was used.

Despite the disadvantages of using qualitative approaches due to subjectivity, this method was selected because it had been previously applied successfully in the study area. The most commongly used method, the Universal Soil Loss Equation (Wischmeier and Smith, 1978), was rejected in view of the inconvenience of using this quantitative approach in areas with different characteristics from those it was developed for. In fact, in the study area, I.C.O.N.A. (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 tm/ha/year(see chapter 2.3.3.5.).

The objective of our study (determining suitable locations for different land uses) was another reason selecting this method, because our aim was to differentiate between high and low susceptible areas, but not to quantify the amount of eroded material.

Degraded slopes in Tertiary materials used as irrigated land or covered by sclerophyllous vegetation have the highest susceptibility values, mainly due to the bad texture and reduced useful depth of its soils, and the high slope percentage. Flat bottom valleys used for non-irrigated arable land or covered by sclerophyllous vegetation also have a high degree of erosion susceptibility, caused by the bad characteristics of the soils, slope and land cover.

In the case of flat bottom valleys, the main erosion process is gully erosion. One of the main reasons for this erosion is the cessation of agricultural land use. The erosion process is extremely noticeable following the abandonment of the land. Thus, due to the static character of the land cover map used, this process was not introduced in the model. As a consequence, the model may present lower susceptibility values than the actual ones in the areas with gully erosion. Nevertheless, this is a local phenomenon, and our results present susceptibility values at regional scale with the homogeneous units as map unit.

7.2.5. Dolines susceptibility

The logistic regression technique has already been used for many environmental purposes, in many cases with more success than multiple linear regression (see chapter 5.2). In addition to this, this study included an attempt to perform a linear regression model between the density of dolines and the susceptibility factors. However, the results were not satisfactory (see cahpter 5.2.4.). This was one of the reasons determining the application of a logistic regression technique for the doline susceptibility map in the study area.

In addition, it is important to stress the main advantage of the technique: the possibility to analyse a qualitative variable (such as the occurrence or not of dolines) as a function of several qualitative and quantitative explanatory variables. This contrasts, with multiple linear regression, which is appropriate only when the dependent variable and the explanatory variables are quantitative and continuous.

Our results corroborate this affirmation as many of the most important variables in the doline distribution were categorical i.e. geology, represented by the different terrace levels. Besides, it allowed us to introduce anthropogenic factors that finally proved to be very important in controlling doline probability, namely location of irrigated land. In addition to this, it was necessary to categorize continuous variables in some cases, since the changes produced from one unit to another are insignificant or are not constant along the range of values of the variable.

This is the case for the thickness of Quaternary deposits or the percentage of permeable layers. Our results suggest that there is a threshold of 30 m thickness of Quaternary cover above which thicker covers reduce the doline probability. Similar results can be found in previous studies (Johnson, 2005; Simón *et al.*, 1998b; Soriano and Simón, 1995). On the contrary, Gutiérrez-Santolalla *et al.* (2005b) did not find a significant influence of the alluvium thickness on the generation of dolines downstream Zaragoza. This may be due to the fact that the influence of the thickness of Quaternary deposits on doline development does not seem to follow a linear tendency, but show a threshold value of 30 m which reduces the doline susceptibility. In addition, the sector downstream of Zaragoza does not have thickness values greater than 30 m (see Map 24).

Several authors have demonstrated, in different mantled karst areas, that the formation of one doline (the ‘‘mother’’) promotes subsurface conditions that favour the formation of additional dolines (the ‘‘daughters’’) in the adjacent area (Cooper and Saunders, 1999; Drake and Ford, 1972; Gutiérrez-Santolalla *et al*., 2005a; Kaufmann and Quinif, 2002; Palmquist, 1979). In the study area downstream of Zaragoza Gutiérrez-Santolalla *et al*. (2005a) found that the dolines show a clear tendency to form clusters.

With respect to this, in agreement with Gutiérrez-Santolalla *et al*. (2005b) it was our opinion that the mapping of areas affected by subsidence is an effective piece of information for subsidence avoidance planning. Consequently, these areas must be considered as areas with high probability of doline development. However, as they pointed out, these maps have some limitations related to the difficulty of mapping all the subsidence areas, as they may be masked by the morpho-sedimentary activity of the fluvial system and anthropogenic fillings. Therefore, the study of the relationship between doline distribution and different environmental factors is very important, since hazardous areas can be better recognised which, with simple mapping approaches, would be considered as non-hazardous.

As a result, the doline probability map created with the Geographical Information System and logistic regression technique contains valuable information for land-use planning at a regional scale. The introduction of three-dimensional information improved the results reasonably, as was demostrated and explained in chapter 5.2.3.2.

On the other hand, there are some limiting factors such as the impossibility of regionalizing some variables and the lack of borehole information in some areas. The first is exemplified by the case of the mentioned salty layers (see chapters 3.1.2. and 5.2.2.), the faults in the Tertiary evaporites or the location of areas where the Tertiary Aquifer discharges in the Alluvial Aquifer (see chapter 5.2.2.). Besides, the mentioned lack of boreholes in the pediments sector upstream of Zaragoza and the Ebro Valley downstream of Zaragoza was also a handicap.

The highest susceptibility values are generally found in the terrace T2, in all the study area, and in the contact area between T2 and T4, in the sector upstream of Zaragoza, with the exception of the areas were the Quaternary deposits are very thick (usually greater than 30 m), which attains low susceptibility values. This last situation exists in a sector north-east of Zaragoza city and inside the city, where very thick Quaternary sediments were assumed in the past. Also, an area upstream of the mouth of the *Jalón* River shows low susceptibility values, due to the very thick Quaternary deposits, despite its location in terrace T2.

In addition to areas with thick Quaternary deposits, the lower susceptibility values are located in areas with a higher percentage of impermeable layers, such as found in terrace T1 upstream of Zaragoza, the surroundings of *Alagón* city and south of Zaragoza. The low susceptibility areas also correspond to areas where there are no irrigation practices, with the exception of the *Logroño* road (upstream of Zaragoza), which has high susceptibility values. This may be explained by the transformation, which this area suffered in the 60s and 70s, due to the industrialization process. This was traditionally a wetland with many shallow depressions used for irrigated agriculture.

It should be noted that the division in categories was intended for visualization purposes, which does not imply a categorization into safe and unsafe areas. In fact, all the covered karst area in particular, and our study area in general, possess a high probability of doline development.

In addition, it would be convenient to continue working in the study area with respect to the subsidence area avoidance for urban planning. An excellent example of management may be found in some countries like Slovenia and China, where governments have founded karst research institutes (Veni, 1999). A good idea for managing the area surrounding Zaragoza city would be the creation of a karst database. This database ought to integrate the karst feature mapping of previous studies performed separately in different areas around the city of Zaragoza by different research groups. There is also a need for integrating information related to the geological, environmental and human factors and the creation of new data in areas with poor information, as is the case of the Ebro Alluvial downstream of Zaragoza and the pediment sector. And finally, but not less important, active cooperation is required between the different research groups and land-use managers.

7.2.6. Groundwater vulnerability

As to groundwater vulnerability, the general approach proposed by the German State Geological Surveys (GLA, Geologisches Landesamt, method), published by Hölting *et al*. (1995), was also applied successfully. One of the main advantages of the GLA method is the availability of the information required for its performance since it only requires general information related to soils, climatology, geology and hydrogeology, which is relatively easy to obtain and to integrate this in the Geographical Information System and Gocad. This was the main reason for selecting this approach.

The development of this methodology within the Geographical Information System is relatively easy, implying simple interpolation between points in order to obtain two-dimensional vulnerability maps. However, as a consequence, the three-dimensional characteristic of the aquifer is not considered. Therefore, groundwater vulnerability maps developed within Gocad should generate more realistic results (although the final result is also two-dimensional) as it takes the three-dimensional geological information into account (Hoppe *et al*., 2006a, 2006b; Lerch and Hoppe, 2006).

The models developed for our study area in present-day irrigation conditions are extremely influenced by aquifer recharge. However, in the case of the model developed in Gocad, this influence is highly smoothed by the 3D interpolation method. In addition, the model developed in ArcGIS, in some sectors, yielded lower values of protection than the ones expected from the characteristics of the aquifer (see chapter 5.3.5.). Thus, although both results follow the same general tendency, the Gocad models generally presents a more reliable mapping. Besides, the Geographical Information System produces less realistic results, showing strong discontinuities, normally less usual for natural processes.

Under natural conditions without irrigation recharge, the model developed with the Geographical Information System tends to exaggerate the protection in some sectors, and to reduce it in others (see chapter 5.3.5.). Thus, when feasible, it is particularly recommended to perform 3D approaches, although they are frequently more time and money consuming. Consequently, the models developed within Gocad were used in the land-use suitability analysis.

In general, the highest vulnerability values are located in the lower terraces with irrigation land use. There are some exceptions, *i.e.* the surroundings of the *Virgen de la Columna* urbanization (*El Burgo de Ebro* municipality), the north-west of Zaragoza and the north of *Alagón*, where medium or low susceptibility values appear, although the land is irrigated. This usually occurs because of high protection values of the subsoil, caused by high thickness of unsaturated Quaternary sediments or high presence of impermeable layers in the lithological profile.

However, the lack of information downstream of Zaragoza city and in the pediment sector, where a different approach was performed, can determine the reliability of the models in these areas. However, the obtained results are satisfactory within their limitations. This is shown by the developed groundwater vulnerability maps, which, especially in the case of the three-dimensional approach, are of great value for supporting land-use management on aregional scale.

7.3. Land-use suitability analysis

7.3.1. Site search analysis

The land-use suitability maps developed with the *Simple Additive Weighting* and *Analytical Hierarchy Process* methods integrated in a Geographical Information System for the surroundings of Zaragoza, are a substantial aid in the land-use management of this city. There is also an additional benefit achieved by integrating geoscientific aspects in the land-use decision process, as demanded by Agenda 21.

The greatest disadvantage of the *Simple Additive Weighting* methods is that they tend to be *ad hoc* procedures with little theoretical foundation to support them. However, since they are easy to use, *Simple Additive Weighting* methods are actually quite widely applied in real-world settings.

A fundamental problem of decision theory is how to derive weights of criteria. A well-known weight evaluation method is the Analytical Hierarchy Process. However, one disadvantage of this method is the inherent subjectivity of assigning preference values between criteria. In addition, the weights derived from these preference values have a profound effect on the results of the suitability analysis. This can be observed in the different results obtained in the two approaches developed in this project (under sustainability aspects and under economical aspects).

Nevertheless, as mentioned in chapter 7.1., it should not be forgotten that land-use decisions are made by managers, implying a certain level of subjectivity. A possible solution to this problem is to establish the preferences of the different stakeholders in order to develop different suitability maps and to combine these to select the most suitable areas.

In addition, in order to avoid inconsistencies when assigning preference values, Saaty (1977) provided a single numerical index (consistency ratio) to check for consistency of the pairwise comparison matrix.

However, in our opinion and following the suggestion of Agenda 21, unless great disagreements between the stakeholders are addressed, the sustainability aspect approach should be performed.

After some talks with different managers in the administration and following the approach under sustainability aspects, our results suggest that, the areas more suitable for sand and gravel extraction are located in the high terraces, and in those terraces covered by pediments where the thickness of resource is relatively high. Besides, these areas are far from natural valuable areas, outside the areas most vulnerable to groundwater contamination, and in soils with poor irrigation capability.

In fact, these suitable areas correspond to the current gravel extraction sites in the region. In addition to areas where the resource is not present, the less suitable areas are located in the low terraces where groundwater vulnerability is higher and water table level is nearer to the surface. Furthermore, several natural areas worth protecting are located near the river.

The irrigation suitability analysis indicates that the more suitable areas are located in a small sector in the south-west of the study area, in a zone where the pediments produce a smooth slope to the terrain, and with low values of groundwater vulnerability and doline susceptibility. The lowest values of suitability correspond to the thickets in the vicinity of the river and protected steppes in the south-east of the area, which also have a high slope percentage.

The best location for new industries is on the pediments and Tertiary sediments outside the natural protected areas, where the groundwater vulnerability and flood risk is lower, although the geotechnical characteristics of the terrain are less favourable, according to the Land Management Planning of Zaragoza (PGOUZ). On the contrary, the worst location is the floodplain with high groundwater vulnerability values and the natural protected areas around the river bed, and other areas in the higher terraces which are more susceptible to doline development.

Finally, the best zones for new location of urban areas are situated in the contact between terraces and pediments south and south-west of Zaragoza. Besides, some sectors along the *Huerva* and *Jalón* Valleys and north or north-east of *La Muela* structural platform achieve good suitability values. The least suitable areas are the steppes in Tertiary sediments and natural areas along the Ebro shores.

Combining all the suitability analyses, it is possible to locate the areas with higher land-use conflict, where several land-uses compete for the terrain. The areas with highest land-use conflicts correspond to the high terraces and pediments, mainly south-west of Zaragoza, where, in general, geo-hazards (groundwater vulnerability, doline and erosion susceptibility) present the lowest values, and many geo-resources (sand and gravel and good agricultural soils) are also present. In addition, these sectors have low slope percentages, which is a limiting factor for many uses, and lack natural spaces of great environmental value.

In fact, these areas are currently undergoing a rapid development in the proximity of Zaragoza, with the construction of a great industrial area (PLAZA) and several urban areas. Nevertheless, the pediment sector is characterized by a lack of geological, hydrogeological and geotechnical information,raising the question of the quality of the models in this sector. Thus, it is recommended to continue the research in this direction, since more borehole information should be available, in view of the current construction activities in the new industrial and urban areas and for the High-velocity railway.

7.3.2. The site selection analysis

The advantages of the concordance methods, such as *PROMETHEE-2*, include the ability to consider both objective and subjective criteria and the requirement for the least amount of information from the decision maker. However, *outranking techniques* require pairwise or global comparisons among alternatives, which is obviously impractical for applications where the number of alternatives/cells in a database ranges in tens or hundreds of thousands. Thus, *PROMETHEE-2*, integrated in a Geographical Information System, was a valuable tool for the site selection analysis where different alternatives should be ranked.

An advantage of outranking methods is the fact that criteria do not need standardization or transformation, processes which reduce subjectivity. However, some decisions should still be taken by the decision-maker, such as *i.e*. the selection of the value to be introduced in the PROMETHEE-2 procedure (maximum, minimum, mean, etc.), the selection of the preference function and generalized criterion and the criteria weights assignation. In our case, the Analytical Hierarchy Process was also used to reduce subjectivity in assigning criterion weights.

It is important to notice the similarity of the results after applying the site search analysis and the site selection analysis. In general, the highest rank positions are present in alternatives located in areas where the site search analysis also presented the highest suitability values.

Performing a *PROMETHEE-2* with the mean values produces a mean result, but the uncertainty in either the input values or the result cannot be quantified. The stochastic approach solves this problem by using probability distributions for the input parameters, instead of single values.

It is our recommendation to use stochastic approaches although, in this case, the process is not absolutely integrated in the Geographical Information System. As a consequence, it is more time consuming, as it implies the assignation of distribution types to all the alternatives in every criterion.

In addition, assigning distribution types is tedious work, since all alternatives require statistical analysis and the selected distribution types must make physical sense, in order to avoid assigning unreal values in the suitability analysis.

In some cases, in order to avoid this problem, the best distribution type, according to the fitting test, was rejected in favour of the alternative more commongly applied to other alternatives. In other cases, it was decided to use the percentage of values instead of assigning a distribution type.

In the extraction site selection suitability analysis, alternative 10 (see Map 65), a real alternative located in the contact between the old terraces and pediments near the airport, is ranked first in both approaches. In fact, there are only a few differences between both the *PROMETHEE-2* and the stochastic *PROMETHEE-2* approaches. An example is the change in ranking between alternative 1 and 2 because of the location of a small part of alternative 1 in an area with use restrictions (constraints).

In the irrigation areas site selection analysis, site number 7 (see Map 66) is rated best in both approaches rate. In general, *PROMETHEE-2* and stochastic *PROMETHEE-2* produce the same first and last ranking. One exception is alternative 9, which changes from ranking 2 to ranking 5, mainly due to the heterogeneity of its values, especially in the case of the groundwater protection criterion. This heterogeneity produces higher mean values when applying *PROMETHEE-2*, which implies a higher ranking in relation to the stochastic approach. Similarly, alternative 10 loses rank position when applying the stochastic approach.

The first rank is different for industrial settlement suitability analysis. However, there are few differences in the SI values and total flows between the first rankings: alternatives 7, 25, 23, 26 and 27 (see Map 67). All these alternatives are located in the areas with higher suitability values in the site search analysis. The worst rankings, alternative 16, 17 and 18, are located inside restricted areas, but also in the proximity of *El Burgo de Ebro* village.

Finally, in urban development suitability analysis, the first rank also varies from alternative number 40 to alternative number 12 (see Map 68). The possible reason is the existence of a small area, inside alternative 12, with low suitability values, which reduces the mean criteria value used in the *PROMETHEE-2*, and, as a consequence, its rank position. On the contrary, in the stochastic approach, these low suitability values present little importance, since they represent the tail end of the distribution. Remarkable is also the case of alternative 16, which shows an increase of 26 rank positions, also caused by the constraints. The alternatives reducing its rank in the stochastic approach, i.e. number 31 and 33, generally have homogeneous middle-good suitability values throughout, which result in a better positioning when applying the mean value in the simple *PROMETHEE-2*.

8. References

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