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SUITABILITY ANALYSIS FOR SAND AND GRAVEL EXTRACTION SITE LOCATION IN THE CONTEXT OF A SUSTAINABLE DEVELOPMENT IN THE SURROUNDINGS OF ZARAGOZA (SPAIN).

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Abstract. Zaragoza city is located in the central Ebro Basin, in the Iberian Peninsula. The fluvial terraces formed by the Ebro River present a valuable resource of sand and gravel deposits. However, taking advantage of these available resources implies conflicts with other land use interests like urban and industrial development as well as agricultural use, which has also traditionally occupied the alluvial terraces. These deposits represent a substantial groundwater resource that should be preserved for future generations.

The development of Spatial Decision Support Systems (SDSS) has greatly assisted efforts for solving land-use conflicts. These systems combine the benefits of Geographic Information Systems (GIS) and decision support methodologies and are therefore suitable to manage sustainable development of urban areas. In this contribution, an extraction suitability map taking into consideration a variety of environmental criteria is created with the help of a SDSS. The method used is the Analytical Hierarchy Process which is integrated in ArcGIS.

Areas most suitable to 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. These areas are far from valuable natural areas, outside areas most vulnerable to groundwater contamination, and beneath soils with poor irrigation characteristics.

Keywords: geo-resources; GIS; AHP; land use management; SDSS; Ebro Basin

Introduction

Zaragoza city is crossed by the Ebro River, the most plentiful river in the Iberian Peninsula (Figure 1). The Tertiary continental sedimentary infill of the Ebro Basin is composed of conglomerates and sandstones at the margins, grading into clays, marls, evaporites and carbonate facies towards the centre of the basin (Benito et al. 1998). In the depo-centre 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.

These fluvial terraces represent a valuable geo-resource in terms of sand and gravel deposits. One of the major issues in geology relates to the transfer of 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 surveys in relation to raw-material modelling refer to the simple location of 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; Kündig 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 also indicated.

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 Spanish National Geological Institute, 1974) developed a series of analogue maps of industrial rocks (*rocas industriales*) 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.

Though there is a tendency to enhance GIS towards 3 dimensional visualisation, development has still not gone so far that complex 3 dimensional bodies can be processed and queried, which is a limiting factor regarding spatial problems that have a strong geological focus. To tackle this problem, we suggest a combined use of a powerful 3 dimensional modelling software and a GIS. The 3D modelling software we used is Gocad (Earth Decision Sciences 2005) which was primarily developed for reservoir construction and characterisation. It allows the creation and 3D-visualization of complex geological bodies and offers functions especially designed for resource modelling computation like volumes and thicknesses. Hoppe et al. (2006) successfully combined Gocad and ArcGIS for spatial modelling and map creation and found that this is a favourable solution for geological modelling.

Here we demonstrate an application of the combined use of Gocad and ArcGIS to evaluate the mining suitability of the Quaternary sand and gravel deposits in the surroundings of Zaragoza.

The exploitation of these resources may give rise to conflicts with other land use interests (e.g. urban and industrial development of the region, agricultural uses, etc.) however, generational equity issues play also a role since these deposits represent a substantial groundwater resource that should be preserved for future generations.

The development of Spatial Decision Support Systems (SDSS) has been a considerable aid in the efforts for solving complex land-use conflicts that commonly appear in a sustainable land-use management. These systems combine the benefits of Geographic Information Systems (GIS) and decision support methodologies and are therefore suitable to support the sustainable development of urban areas.

Study area description

The study area is located in the central part of the Ebro basin in the Aragon region, Spain. This 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 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

This is a highly dynamic economic axis and densely populated area within the Iberian Peninsula.

Zaragoza City is crossed by the Ebro River, the Gállego River and the Huerva River (Figure 1). The terraces of these three rivers and the Jalón River, a tributary of the Ebro on the right bank, represent a valuable geo-resource in terms of sand and gravel deposits. These raw materials are used mainly for infrastructure and construction purposes and are the only ones exploited nowadays in the area of study. Gypsum and salt are also worked in the surroundings.

Sand and gravel extraction is one of the main sub sectors 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 2).

According to the geological map from the ITGE, there are eight levels of terraces in the study area (Figure 3). 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 due to their extent and the favourable characteristics of the materials (Manso et al. 2001). The pediments (glacis) are also deposits of sand and gravels, but are not interesting for the extraction industry due to their low quality.

Terrace T4 was deposited during the Upper Pleistocene. In the study area, 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 removed 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 in the study area is between 20 and 25 m. The surficial extent of this terrace in the study area 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 of Zaragoza and occupies an area of about 6 km^2. T6 is more disseminated in the study area, especially downstream of Zaragoza.

The low market value of this resource determines the local characteristic of this activity, since long distance transport of this resource is not economic. The total amount of resource in the municipality of Zaragoza is quantified in 3,012 million 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.

Methodology

Sand and gravel deposits modelling

The 3D geological model of Quaternary deposits in the study area was developed with Gocad to map the location of sand and gravel deposits in the vicinity of Zaragoza. This model was created using information from more than 900 boreholes (including the Gállego area). The information was obtained from a water points database from the Ebro Basin Authority (CHE) called IPA and complimented with 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 outline of the area covered by the geological 3D model is determined by the nature of the scientific questions to be answered. Besides its use to model the sand and gravel deposits it was further intended to be used for a model of the doline development as well as for a groundwater vulnerability study (Lamelas et al. 2007a, b). For these reasons, the construction of the 3D model was restricted to the greyed area of Figure 4 which comprises the Quaternary deposits of the Ebro Valley, the region’s dominant aquifer, and the glacis (Figure 1). Nevertheless, it should be noted that the accuracy of the model is determined by the limited information available concerning the Ebro alluvial deposits downstream of Zaragoza (Figure 1) and glacis or pediments located in the right back of the Ebro River upstream Zaragoza.

The geological information taken from the boreholes available was processed in the following way (Lamelas et al. 2007b; Lamelas et al. IN PRESS):

- Structured data storage in a database.
- Evaluation and "cleaning" of borehole data. Cleaning here refers to the removal of boreholes with unreliable, incomplete or missing 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 (Figure 4). Three cross-sections were defined parallel to the strike of the valley.
- Systemisation of the borehole lithology by help of the cross-sections. Since the objective was to establish a model of the Quaternary, the encountered layers were coded as either Quaternary or Tertiary where the top of the Tertiary is usually encountered if gypsiferous layers are met. The top of the Tertiary could then comfortably be queried from the database and be exported to a text file.
- The query results were imported into Gocad as points distributed in a three dimensional space and then combined to a surface object.

Figure 5 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 was filled with the lithological information of the boreholes which, in turn, have allowed assessments with regard to the amount of available geo-resources like sand and gravel.

To fill the space in between the upper and lower boundary, Gocad offers the sGrid (stratigraphic grid) object, which is a collection of initially regularly spaced cells which fill the three dimensions with information. However, a sGrid can be deformed such that it perfectly suits geometrical boundary conditions. The deformed sGrid of the study area and a detail showing the irregularity of the grid can be observed in Figure 6.

Next, the sGrid representing the geological body was filled with information. Therefore the layers encountered in the boreholes were first assigned with numerical values representing the grain sizes of a specific soil type. Since the position of every borehole sections in the 3D space are known, this information could be transferred to the corresponding position in the sGrid. A subsequent interpolation in the sGrid finally filled the 3D space. The interpolation method used was the discrete smooth interpolation algorithm (DSI) which belongs to the core functionality of Gocad.

In a final step, a script was applied to the sGrid, allowing a differentiation of areas cells belonging to potential sand and gravel deposits and thus allowing the computation of the thickness of available sand and gravel deposits. Finally, the information of the sand and gravel thickness was projected as a point on a flat 2D surface which in turn was then imported by ArcGIS to be transformed to a map (Figure 7). The same methodology was used for the creation of a model of overburden material thickness, that is, material located above the sand and gravel deposits, which cannot be used for construction purposes. A map of the overburden thickness is a crucial factor regarding the exploitation of a deposit since the removal of the overburden to get access to the deposit causes costs whereas the overburden itself has practically no economic value.

Extraction site suitability analysis

The GIS-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. 2006; Lamelas et al. 2006, Malczewski 2004; Marinoni and Hoppe 2006).

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 MCDM 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 data oriented. Multiattribute techniques are also referred to as 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).

Additive decision rules are the best known and most widely used MADM (MultiAttribute Decision-Making) methods in Geographical Information System based decision-making. According 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 Analytical 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 (e.g. Compromise programming).
- 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 (e.g. Promethee, Electre).

Despite the existence of diverse methodologies, 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 (Gilliams et al. 2005).

Thus, several steps have to be covered in the suitability analysis (Figure 9). 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.

- Definition of criteria weights: in our case, with the use of AHP.

In this contribution a pixel based site search analysis is performed; the used pixel size is 20 x 20 m. The SAW method integrated in ArcGIS 9.1 (ESRI 2005) is applied in order to create suitability maps for the location of new extraction sites (Figure 9). In SAW 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. 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.

Definition of constraints

The first step is the 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, 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: Imperial Canal and other canals, roads and train rails (infrastructure and area of protection as defined by the Spanish Roads Law and Spanish Railway Sector Law). This information was extracted from the topographic maps, scale 1:25,000, from the National Geographical Institute (IGN), imported to ArcGIS and updated (Figure 10).

- 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 (Figure 10).

- Industrial areas: the source is a database of industrial areas from the Aragon Institute of Public Works (IAF, Instituto Aragonés de Fomento). This information can be downloaded from the internet (http://www.iaf.es, Figure 10).
- 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 (Figure 11).
- Cattle tracks: tracks traditionally used by the seasonal migration of livestock which are protected (Figure 11).
- 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). 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 (Figure 11).
- Land management planning from Zaragoza city (PGOUZ): according to this planning, extraction is not feasible in some areas.
- Natural resources planning of the thickets and oxbows of the Ebro River: according to this planning, there are some areas not permitted for extraction purposes.

Definition of variables

A variety of social, economical and environmental factors, playing an important role in the decision making process for the location of new sand and gravel extraction sites, are taken into consideration. These variables are:

- Distance to roads: the Environmental Impact Assessment Law (EIA) states that extraction sites should be >2 km distance from roads.
- Distance to nuclei with population over 1000 inhabitants: extraction sites should be >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 Special Protection Areas for birds, Special Areas for Conservation, habitats which are not strictly restricted, but require environmental impact assessment prior to their utilization. It also includes other areas as sites of geological interest, wetlands, areas of the natural resources planning of the thickets and oxbows of the Ebro River with no strict restrictions, etc. Besides, it includes the Hydraulic Public Domain.
- Groundwater vulnerability: a model developed within Gocad by Lamelas et al. (2007b) was introduced in the process. This factor is considered, since sand and gravel exploitation implies the reduction of the aquifer protection cover. Thus, areas with higher groundwater vulnerability should be protected from being exploited.
- 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 by Lamelas et al.

(2007a, b) for doline susceptibility and groundwater vulnerability assessment has been applied.

- Irrigation capability of the soils: it is highly recommended to preserve all resources in the study area. Thus, areas covered by soils with good irrigation capability should be avoided for extraction site location. A model developed by Lamelas (2007) was used.

- Geo-resource location: the sand and gravel thickness model is used. Deposits with a high thickness imply a higher exploitable volume of the deposit so that the surface area of the area that is mined can be reduced.

- Overburden: according to the model developed. This factor is introduced since the removal of the overburden to get access to the deposit causes costs.

Transformation of variables into criteria

These variables should be standardized before they can be transformed into criteria. According to Malczewski (1999), the classification (standardization) approaches can be classified in: Linear Scale Transformation, Value/Utility Function, Probabilities, Revised Probabilities and Fuzzy Set Membership. The standardization method used here may be inserted in the subjective scales approach since the variables are classified in subjective ranges. These ranges are selected following indications by law or the classes already determined in the existing 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.

Finally, after some discussions with technicians at the Zaragoza council, Ebro River Authority and Aragon Government the categories used were (Figure 12):

- 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 Lamelas et al. 2007b): (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 Lamelas 2007): (i) Calcaric Fluvisols = 1; (ii) Petric Calcisols = 2; (iii) Calcaric Cambisols = 3; (iv) Haplic Gypsisols = 4; (v) Calcaric Regosols = 5; (vi) Haplic Solonchaks = 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 difference 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.

Assigning decision weights and mapping

A fundamental problem of decision theory is how to derive weights of a set of criteria according to their importance. A well-known weight evaluation method is AHP proposed by Saaty (1977). This method 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. The procedure consists of three major steps: generation of the pairwise comparison matrix, the criterion weight computation, and the consistency ratio estimation (Saaty 1977).

As mentioned above, 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 1).

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 need to be computed (Marinoni 2004). According to Saaty and Vargas (1991), it is sufficient to compute the weights using the eigenvector resulting from the largest eigenvalue since it 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) 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

$$CR = CI/RI \quad (1)$$

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

$$CI = (\lambda max - n) / n - 1 \qquad (2)$$

where λmax 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 integration of the AHP in GIS combines decision support methodology with powerful visualization and mapping capabilities which in turn should considerably facilitate the creation of land-use suitability maps (Marinoni 2004). 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. Table 2 shows the matrix and 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 well below 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. 2006). In this case study preference values have been defined after conversations with different stakeholders from the Zaragoza Council, Aragon Government and Ebro River Authority. The highest weight has been assigned to the location of the resource (value 0.280), as, in this case, this factor extremely determines the possibility to extract (Table 2).

The ground water vulnerability (0.187), natural protected areas (0.187), irrigation capability of the soils (0.111) and groundwater depth factors (0.111) have also very high values, which reasonably reflect sustainability issues. All other criteria received much smaller values (Table 2).

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 SAW method.

Results

Figure 7 and 12 show the sand and gravel deposits thickness and overburden thickness models developed within Gocad. 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 is 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 (Figure 7), 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 reliable as elsewhere. 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 12 shows the suitability map for extraction location. The black sections indicate the areas where extraction is not possible due to the constraints. Although the suitability analysis sometimes presents good values, the constraints imply that these areas cannot be exploited due to any restriction. The areas more suitable to sand and gravel extraction (light grey 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 (dark grey 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 (Figure 7) where very thick deposits of sand and gravel are found. However these sites also have high groundwater vulnerability and are close to valuable natural areas.

Discussion and conclusions

The development of a 3D geological model of the study area was of great value in the case of the sand and gravel resources model because of the three-dimensional characteristics of this resource. 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 a better spatial understanding of the sand and gravel resources in the study area.

However, taking advantage of these available resources implies conflicts with other land use interests. SDSS provide a considerable aid in the effort of solving land-use conflicts that commonly appear in sustainable land-use management. These tools combine the capabilities of Geographical Information Systems and decision support tools in terms of multi-criteria evaluation methodologies. 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 valid methodologies to support the land-use decision process.

The land-use suitability map developed with the SAW and AHP methods integrated in a GIS for the surroundings of Zaragoza is a substantial aid in the extraction site 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 SAW methods is that they tend to be ad hoc procedures with little theoretical foundation to support them. However, since they are easy to use, SAW 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 and its complexity in the computation of the criteria weights.

Nevertheless, as mentioned above, 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.

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Figures.

Figure 1: Geomorphology of the study area (after Lamelas et al. 2007a).

Figure 2: Large sand and gravel extraction site in the vicinity of Garrapinillos in Terrace level T4. November 2005.

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Figure 4: Area and boreholes for sand and gravel deposits model.

Figure 5: Interpolated top of the Tertiary in the study area (exaggeration factor 50). The Quaternary layers are removed. Top-view from northwest, bottom-view from south.

Figure 6: Deformed sGrid for the study area (vertical exaggeration factor: 50). In the inset detail can be observed the irregularity of the grid due to the deformation by geometric constraints.

Figure 7: Sand and gravel deposits thickness.

Figure 8: Land-use suitability analysis approaches.

Figure 9: Workflow of the land-use suitability analysis.

Figure 10: Extraction restrictions: infrastructures, urban and industrial areas.

Figure 11: Extraction restrictions: Nature Reserve, cattle track, old extraction sites.

Figure 12: Result from the site search suitability analysis and criteria values.

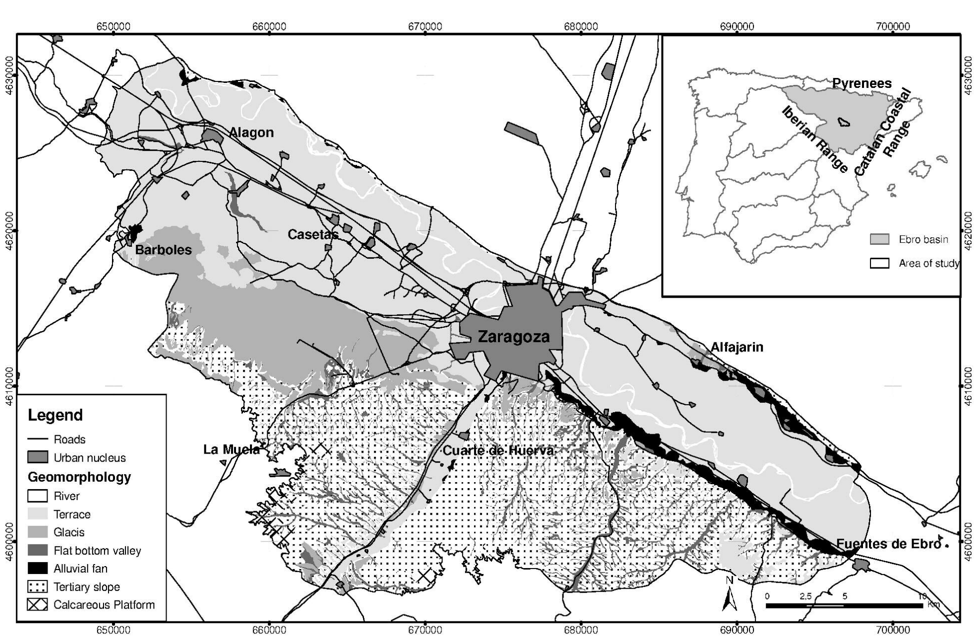
Tables.

Table 1: Scale for comparisons (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

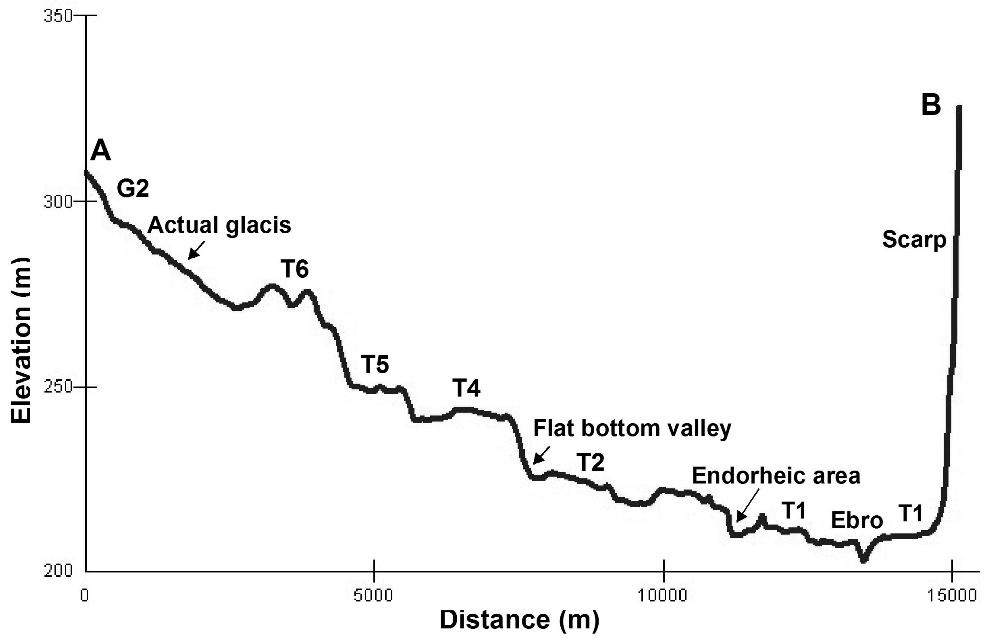
Table 2: Pairwise comparison matrix, criteria weights and consistency ratio for extraction location.

Preference matrix	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**Weight**
A. Distance to extraction	1.00	0.20	0.14	0.33	0.14	0.50	0.12	0.20	1.00	0.022
B. Groundwater depth	5.00	1.00	0.50	4.00	0.50	4.00	0.33	1.00	5.00	0.111
C. Groundwater protection	7.00	2.00	1.00	6.00	1.00	6.00	0.50	2.00	7.00	0.187
D. Distance to nuclei	3.00	0.25	0.16	1.00	0.16	2.00	0.14	0.25	3.00	0.043
E. Distance to natural areas	7.00	2.00	1.00	6.00	1.00	6.00	0.50	2.00	7.00	0.187
F. Distance to roads	2.00	0.25	0.16	0.50	0.16	1.00	0.14	0.25	2.00	0.032
G. Resource thickness	8.00	3.00	2.00	7.00	2.00	7.00	1.00	3.00	8.00	0.280
H. Irrigation capability	5.00	1.00	0.50	4.00	0.50	4.00	0.33	1.00	5.00	0.111
I. Overburden thickness	1.00	0.20	0.14	0.33	0.14	0.50	0.12	0.20	1.00	0.022

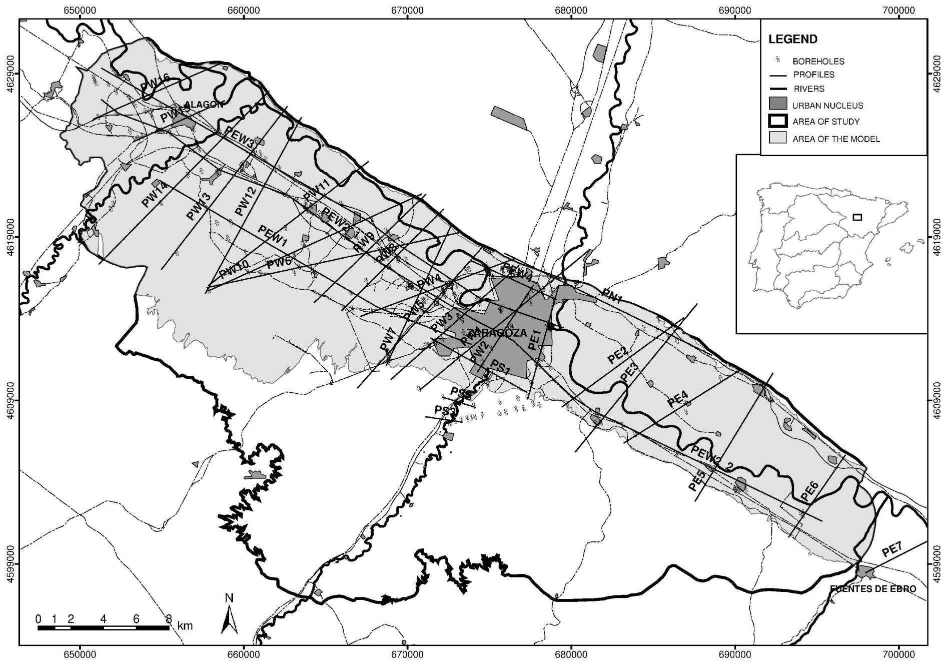


Geomorphology of the study area (after Lamelas et al. 2007a).
170x110mm (600 x 600 DPI)

Large sand and gravel extraction site in the vicinity of Garrapinillos in Terrace level T4. November 2005.
722x541mm (72 x 72 DPI)



Profile of the Ebro River terrace levels upstream Zaragoza. T= Terrace; G= pediment or glacis.



Area and boreholes for sand and gravel deposits model.
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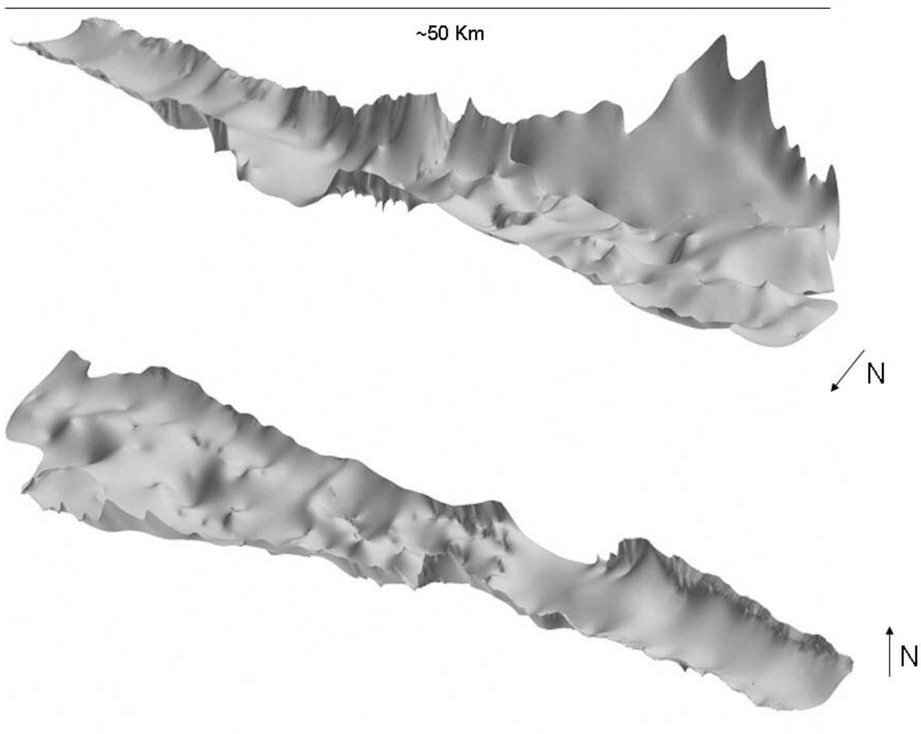
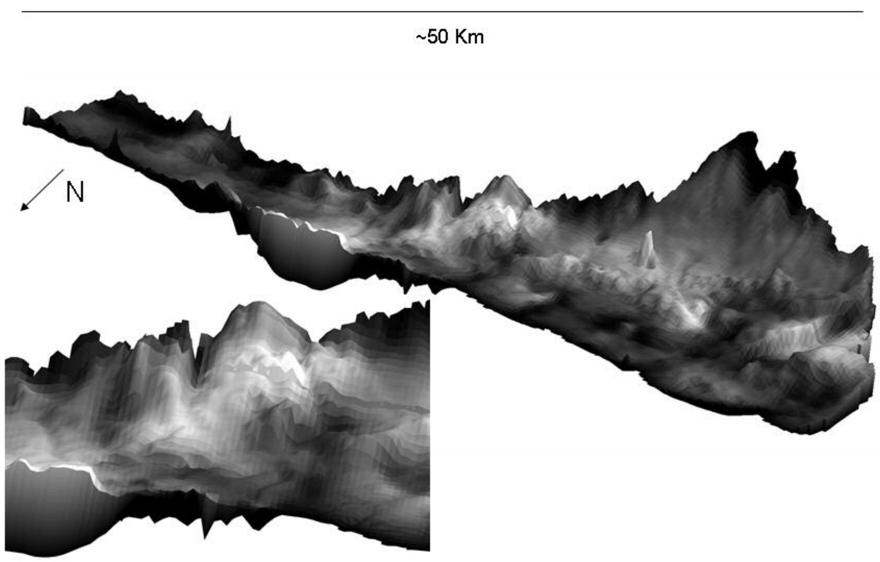
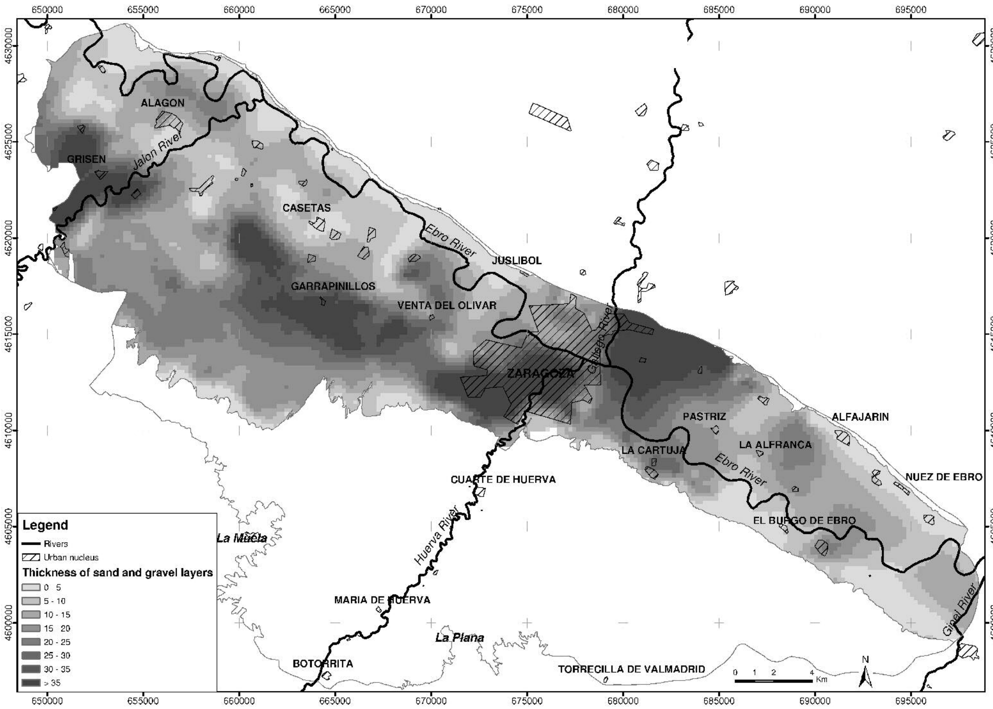


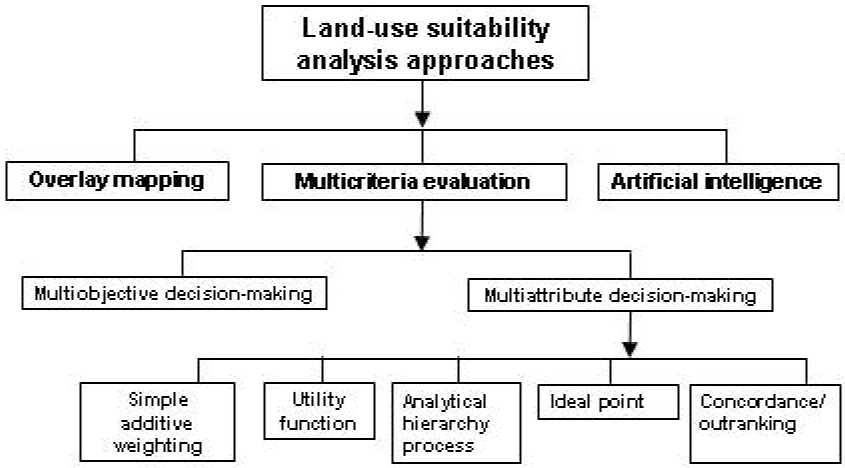
Interpolated top of the Tertiary in the study area (exaggeration factor 50). The Quaternary layers are removed. Top-view from northwest, bottom-view from south.
254x190mm (96 x 96 DPI)



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.
254x190mm (96 x 96 DPI)



Sand and gravel deposits thickness.
297x210mm (600 x 600 DPI)



Land-use suitability analysis approaches.
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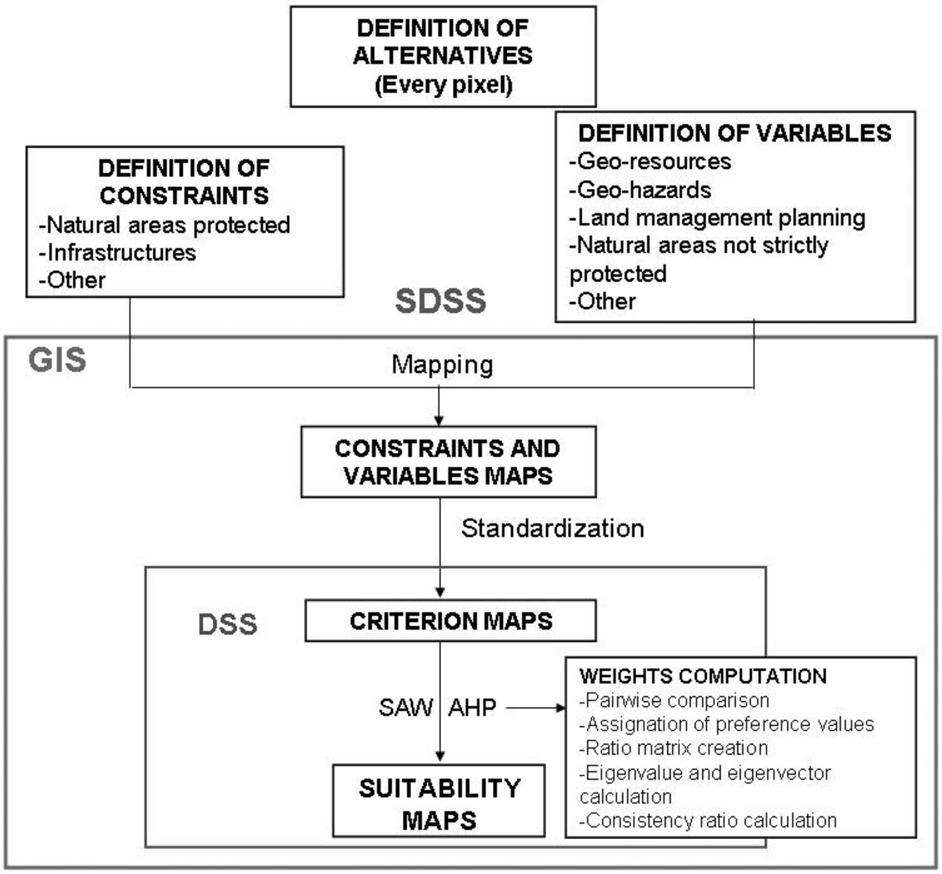
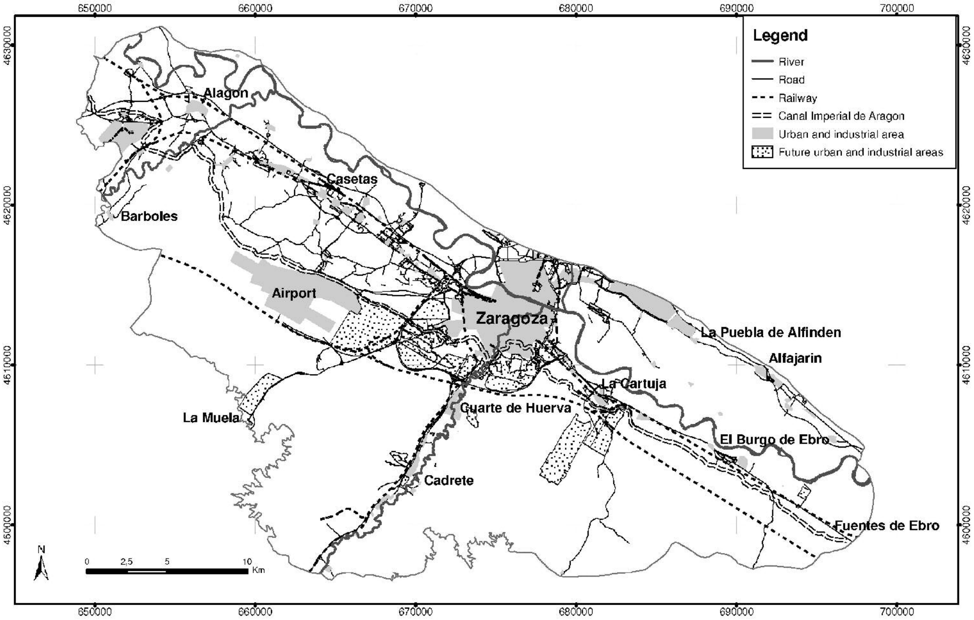
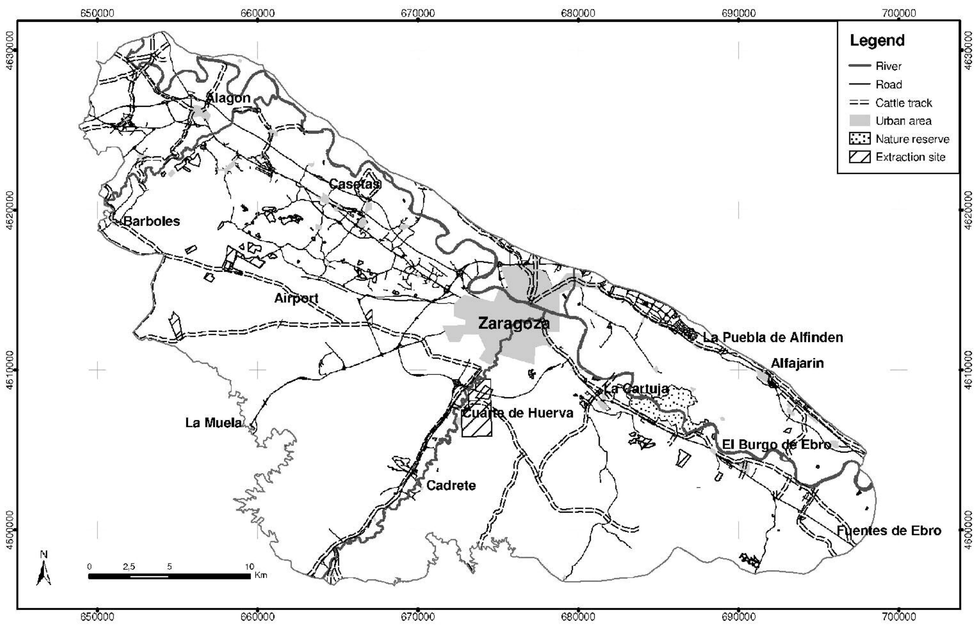


Workflow of the land-use suitability analysis.
211x190mm (96 x 96 DPI)



Extraction restrictions: infrastructures, urban and industrial areas.
170x110mm (600 x 600 DPI)



Extraction restrictions: Nature Reserve, cattle track, old extraction sites.
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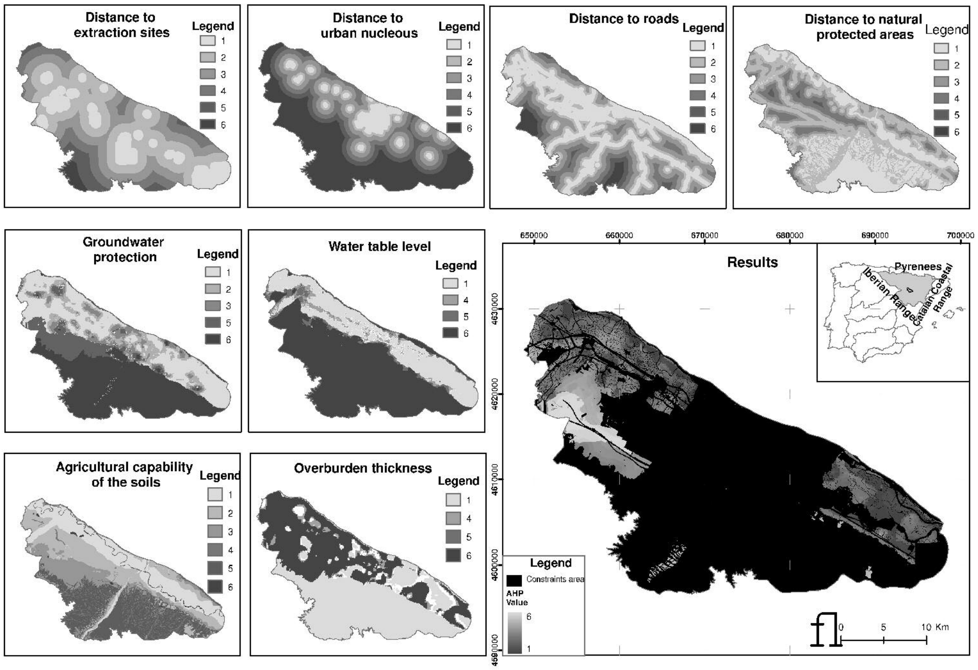

Result from the site search suitability analysis and criteria values.
296x210mm (600 x 600 DPI)