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Groundwater vulnerability map for the Ebro alluvial aquifer between Jalón and Ginel tributaries (Spain).

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Abstract

The Quaternary deposits of the Ebro Basin in the surroundings of Zaragoza (Spain) form an unconfined alluvial aquifer with a high degree of permeability and low thickness of unsaturated materials. This fact causes a high degree of vulnerability to contamination which implies consequences for land-use decisions and the risk management of existing industrial facilities. In addition, 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 low cost. Thus, the development of groundwater vulnerability maps have great importance in a regional planning process.

Consequently, groundwater vulnerability maps have been developed following a method proposed by the German State Geological Surveys. In this paper the methodology developed within ArcGIS and Gocad, a two dimensional and three dimensional software, respectively, is presented. Although the results obtained within GIS (Geographical Information System) are acceptable it is to say that the 3D model improves considerably the final product.

Keywords: groundwater; geo-hazards; GIS; Gocad; Ebro Basin; Spain

Introduction

The city of Zaragoza is located in the central Ebro Basin (Spain). It is crossed by the Ebro river and two of its main tributaries, the Gállego and Huerva rivers (Figure 1). This is one of the reasons of its fast urban and industrial development

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during the last decades: existence of superficial and ground water in addition to its strategic position in the middle of four dynamic economic axes within the Iberian Peninsula.

In the area between Jalón and Ginel rivers, tributaries of the Ebro river located upstream and downstream Zaragoza respectively, the fluvial terraces formed by the Ebro represent a substantial groundwater resource that should be preserved for future generations.

Figure 1: Map of the study area.

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).

In this sense, a first step to carry out is vulnerability mapping. 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.

If a revision of methodologies is made, it can be observed that most models deal with intrinsic vulnerability. They usually apply qualitative weighting methods and

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the main factor are related to the geological, hydrological and hydrochemical characteristics of the aquifer and the materials above it.

An example is the DRASTIC system developed by Aller et al. (1987) which considers the more important mappable technical parameters (factors) that affect groundwater pollution potential: depth to water (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, in scale 1/100,000, was based on static factors, like 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). Afterwards this areas of descriptive nature were evaluated to obtain diagnosis maps of groundwater vulnerability based on lithological characteristics and thickness of saturated zone.

Finally, based on the DRASTIC system and the addition of data from variables such as land use/land cover to the rest of variables applied in the mentioned method, Fritch et al. (2000) applied subjective numerical weightings according to each variable´s relative importance in groundwater pollution susceptibility in Paluxy aquifer in Central Texas (United States).

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 like EPIK (Doerfliger 1996; Doerfliger and Zwahlen 1998) and REKS (Malik and Svasta 1999) were specially developed for karst.

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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. Here, a general approach proposed by the German State Geological Surveys (GLA- Geologisches Landesamt- method) proposed by Hölting et al. (1995) is applied. It deals with intrinsic groundwater vulnerability and considers karstic conditions of the study area which give rise vulnerabilities.

Methodology

The basic idea of Hölting et al. (1995) is that the effectiveness of all natural processes in the protective cover for reducing contaminant concentration is mainly dependent on the travel time. As a consequence, the protective function is dependent on the main factors which control the travel time: the thickness of each stratum and the properties of the materials (Goldscheider et al. 2000).

In relation to this, the protective function of the upper soil is assessed according to its effective field capacity (B value).

In the case of the subsoil, the protective function 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 shows the following formula:

$$S = (B + (\sum M*G))*W \qquad (1)$$

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An additional protective function term can be included for artesian conditions and for a perched aquifer above the aquifer in question. These conditions are not present in the study area so these two factors are not included in the model.
The final value is called “protective function, total score” and it is classified into five categories, from very low to very high protection, based on experience (Table 1).

Table 1: Classification of protective function total scores (after Hölting et al., 1995).

It was our intention to compare the results of applying this model completely in a Geographical Information System (GIS) (the used GIS is ArcGIS 9.1 by ESRI 2005), hence in a 2D environment, or using a 3D software, Gocad (Earth Decision Sciences 2005). This program was previously used to create a 3D geological model for the study area (see Lamelas et al. 2006).
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; another only including the natural conditions of the area. This process was made twice, inside ArcGIS 9 and Gocad, so finally 4 different models are presented.

Results

The basic difference between the groundwater vulnerability assessment based on GIS and the solution provided with Gocad is that the latter approach takes full advantage of the 3 dimensions of the subsurface. However there are some aspects

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that necessarily should be performed within GIS and later on are introduced in the Gocad process. These refers to the protective function of the upper soil (B value), the amount of recharge (W value) and the water table model. In this section, first the development process of these three models is explained to enter afterwards deeper in the groundwater vulnerability maps developed within GIS and Gocad.

The protective function of the upper soil: the B value

For the assessment of the effective field capacity of the soil the information from the Microleis system (de la Rosa and Magaldi 1982) was used. This system includes a relationship between different textures of the soils and field capacities that was developed for Mediterranean soils from a huge database.

Previously and following a geosystemic point of view of the Landscape Science, a morpho-edaphic unit map had been created (Figure 2). Its basis were the landscape units (Lamelas et al. 2006).

The information about texture of soils was extracted from several studies carried out in the area at a more detailed scale (Machín and Navas 1994, 1995, 1998). The different morpho-edaphic units with their effective field capacity and corresponding B value are presented in table 2. For the regionalisation of this values see Figure 3.

Figure 2: Morpho-edaphic units map.

Figure 3: Map of the B value according to Hölting et al. (1995).

Table 2: B value for the different types of soil (after Hölting et al., 1995).

The amount of recharge: the W value

Precipitation and evapotranspiration models for the study area have been developed using information from the National Meteorological Institute (INM,

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Instituto Nacional de Meteorología). This information belongs to a series of 50 years 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 (MOPT 1993, 1996). This covers the requirements of the W.M.O. (World Meteorological Organization) that determine a minimum of 30 years period of measurements for characterizing a climatic variable as precipitation and evapotranspiration (W.M.O. 1967). The data about evapotranspiration was obtained with the Thornthwaite (Thornthwaite 1948) method that only needs data about the mean monthly temperature to be calculated.

Later, this information has to be interpolated in order to obtain a continuous surface for the project area. Interpolation procedures can be simple mathematical models (inverse distance weighting, trend surface analysis, Thiessen polygons, etc.), or more complex models (geostatistical methods, such as kriging and thin plate splines). Here, the poor amount of climatic stations with long period data (9 and 7 for evapotranspiration and precipitation respectively) and their heterogeneous distribution along the study area (see Figure 4) was a handicap for the regionalisation of the meteorological data. This problem was solved by enlarging the area to be interpolated (with 27 and 51 evapotranspiration and precipitation stations respectively) and the use of a global methodology, a multiple regression analysis between the meteorological variables and continuous geographical variables (altitude, latitude, continentality, solar radiation).

Figure 4: Map of the locations of meteorological stations.

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This deterministic method used by several authors (Ninyerola et al. 2000; Vicente and Saz-Sánchez 2002) can be seen as an alternative to classical interpolation techniques when spatial information is available. In this case, the following spatial information has been 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 homoscedasticity) and applying the subsequent transformations to the data, the distance to Mediterranean Sea and the elevation above see 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 (Figure 5).

Under natural conditions (without irrigation) as the precipitation is lower than evapotranspotation all the area takes the highest W value implying high protection. However, for the recharge under irrigation conditions also an approximation to the irrigation amount was performed.

A data base with the available water resources assigned by the Ebro River Authority (*Confederación Hidrográfica del Ebro, CHE*) to every Agrarian Administrative Division (*Comarca agraria*) and irrigation system was available (Cruz et al. 1997).

Besides, a cartography of irrigated areas with information about irrigation systems developed by CHE is available from

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http://oph.chebro.es/ContenidoCartoRegadios.htm. This map was combined with the Agrarian Administrative Division Map (Comarcas map), and the values of water availability were assigned to every system in every Comarca. 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.

Figure 6 shows the recharge values after adding precipitation and irrigation and subtracting evapotranspiration and the W value for the model taking irrigation into account.

Figure 5: Mean annual precipitation and evapotranspiration models.

Figure 6: Recharge amount and W value under anthropic conditions.

The water table model

For the determination of the unsaturated zone a model of the water table is needed so that the layers which are going to take part in the protective function can be specified.

The information about water table level was obtained from the Water Points Inventory (spa. *IPA*) of the Ebro Basin Authority (CHE). In this case, only the points with more than 10 measurements were selected. The mean (irrigation conditions) and minimum (without irrigation) water table level values were queried from the database and interpolated with ordinary kriging. Figure 7 shows both water table models.

Figure 7: Water table models.

The Groundwater vulnerability within GIS

Figure 8 shows a sketch of the working steps within GIS. First of all, two maps have to be developed: the protective function of the soil (B value) and subsoil

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(M*G value), respectively. Then, an addition of both maps is performed with the raster calculator of the GIS. Afterwards, the result is multiplied by the aquifer recharge mapping created (W value) following formula 1.

Figure 8: Scheme of the Groundwater vulnerability model (after Hölting et al., 1995) developed within GIS.

Consequently, for the development of the model within GIS, the protective function of the subsoil in the unsaturated zone have to be performed. The unsaturated zone subsoil, consisting of granular, non-lithified material, is the layer below the topsoil and above the water table. Its protective function is calculated according to its grain-size distribution, which is also related to its permeability and its thickness (M*G value).

The information of subsoil was obtained from the *IPA*. This information was completed with several boreholes collected from different private enterprises (Control-7, Entecsa, Z-amaltea, CTA, ESHYG) and from some previous studies carried out for the construction of several roads (M.O.P. 1967, 1970, 1973, 1994, 2000, 2003). Figure 9 shows the heterogeneous location of the boreholes in the alluvial and the lack of information mainly in the area downstream Zaragoza, thus determining a worse quality of the model in this area.

Figure 9: Location of the boreholes in the alluvial aquifer.

In Tables 3 are presented the different protective values assigned to different description 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 has to be calculated twice as the water table varies from natural

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conditions (that is without taking into account irrigation) to anthropologic and actual conditions (taking irrigation into account; Figure 10).

Afterwards, the protective values of the boreholes are interpolated. In this case a simple kriging interpolation within the GIS has been used to obtain two continuous surfaces, one taking into account irrigation water and another under natural conditions without irrigation (Figure 10). The final groundwater vulnerability models are shown in Figure 11.

In the case of the 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 El Burgo de Ebro, the north-west of Zaragoza and the north of Alagón (Figure 1), where medium or low susceptibility values appear, although irrigation is present. 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.

The values of protection improve considerably in the case of the model under natural condition without support 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 the 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

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sediments is present, but the vulnerability is high, due to the elevated permeability of the layers.

Table 3: 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.

Figure 10: M*G value interpolation.

Figure 11: Groundwater vulnerability maps developed within ArcGIS.

The groundwater vulnerability in Gocad

A 3D approach requires some effort in terms of considering a variety of geometric boundary conditions. In our case the geometric body under consideration is the Quaternary. While the upper boundary of the Quaternary could be easily defined with the Digital Elevation Model the lower boundary in terms of the Quaternary-Tertiary border was constructed with the information of about 400 boreholes. 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 deformed such that it perfectly suits geometrical boundary conditions. Figure 12 shows the definition of a regular sGrid and its deformation by geometric constraints. Please note that all sGrid cells outside the study area were declared as ‘dead cells’ thus indicating that they are to be excluded from further computations.

Next, the geological body was filled with information. Therefore, the layers encountered in the boreholes were assigned with a value taken from table 3 (G-value). These G-values were then interpolated within the sGrid 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.

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Besides the G value property a sGrid object can hold various other properties. To keep all information which is needed for the groundwater vulnerability calculation in one object, additional properties (B, W values) were added to the sGrid. Moreover, help properties were introduced which helped to distinguish between distinct areas. For instance a Boolean property was added which helped to distinguish between layers above and below the groundwater table. All cells of the sGrid above the groundwater table were given a value of 1 whereas the rest was given a value of 0.

Then a script was applied on the sGrid, allowing a user defined computation of the protective function for each column of the sGrid. Figure 13 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 ground water vulnerability respectively (Figure 14).

Figure 12: Gocad regular sGrid definition. a) top view of sGrid with outline of study area, b) regular sGrid before deformation, c) lower and upper surfaces of Quaternary body, d) deformed sGrid (vertical exaggeration factor: 50).

Figure 13: Example calculation for one column of a sGrid object. According to table 1, a value of 1160 is equal to a medium protective function of the unsaturated zone (after Lerch 2005).

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

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is the case of the meander at the west of Zaragoza. This sector presents relatively high thickness of Quaternary deposits, high thickness of unsaturated materials and a high percentage of impermeable layers. Thus, the Gocad model present in this sectors more reliability protection values according to the characteristics of the aquifer. Similar cases can be observed i.e. at the south-east of Casetas, at the north east of Alagón in the confluence of the Jalón and Ebro Rivers and in the surroundings of La Cartuja (downstream Zaragoza).

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 El Burgo de Ebro. In this sector, low thickness of unsaturated deposits and low percentage of impermeable layers are present, thus implying very low protection values, as the Gocad model suggests, and no medium and high protection values, as the ArcGIS model suggests.

Figure 14: Groundwater vulnerability maps developed within Gocad.

Discussion

One of the main advantages of the GLA method is the availability of the information required for its performance as it only required general information related to soils, climatology, geology and hydrogeology which is relatively easy to obtain and introduce in the GIS.

The development of this methodology within GIS is relatively easy implying simple interpolation between points in order to obtain two-dimensional vulnerability maps. As a consequence, the three dimensional characteristic of the aquifer is not considered. Therefore, groundwater vulnerability maps developed

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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. 2006).

The models developed for our study area in the present-day conditions with irrigation are extremely influenced by the recharge of the aquifer. 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, presented lower values of protection than the ones it should have presented, according to the characteristics of the aquifer. Thus, although both results follow the same general tendency, the Gocad models present, in general, more reliability 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 other ones. Thus, when feasible, it is extremely recommended to perform 3D approaches, although they are frequently more time and money consuming.

Due to the lack of information downstream Zaragoza the reliability of the model in this sector is certainly fairly low. However, with its limitations, the results obtained are satisfactory as the groundwater vulnerability maps developed, especially in the case of the three dimensional approach, are of great value for land-use management at regional scales.

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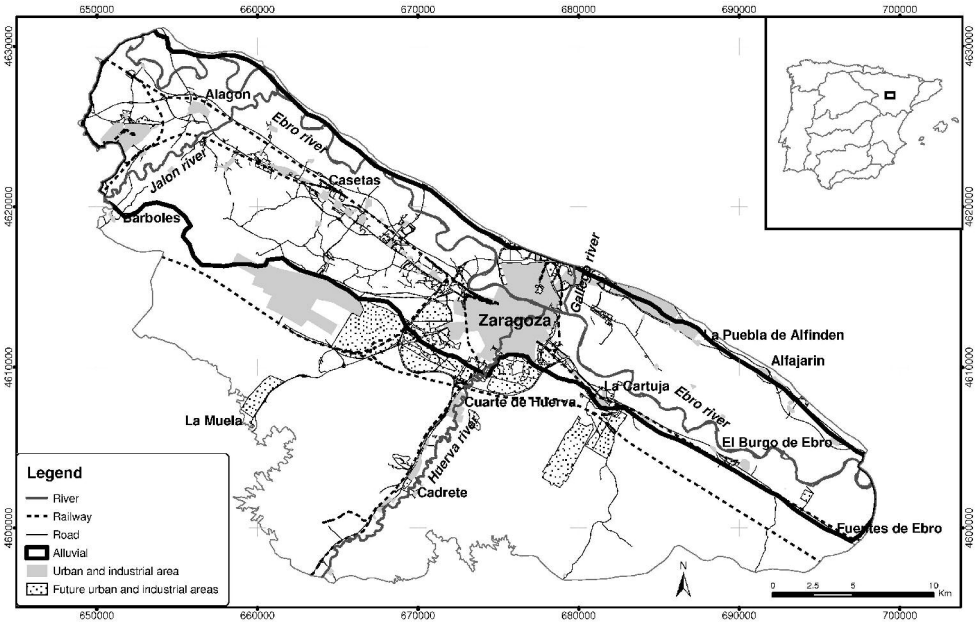

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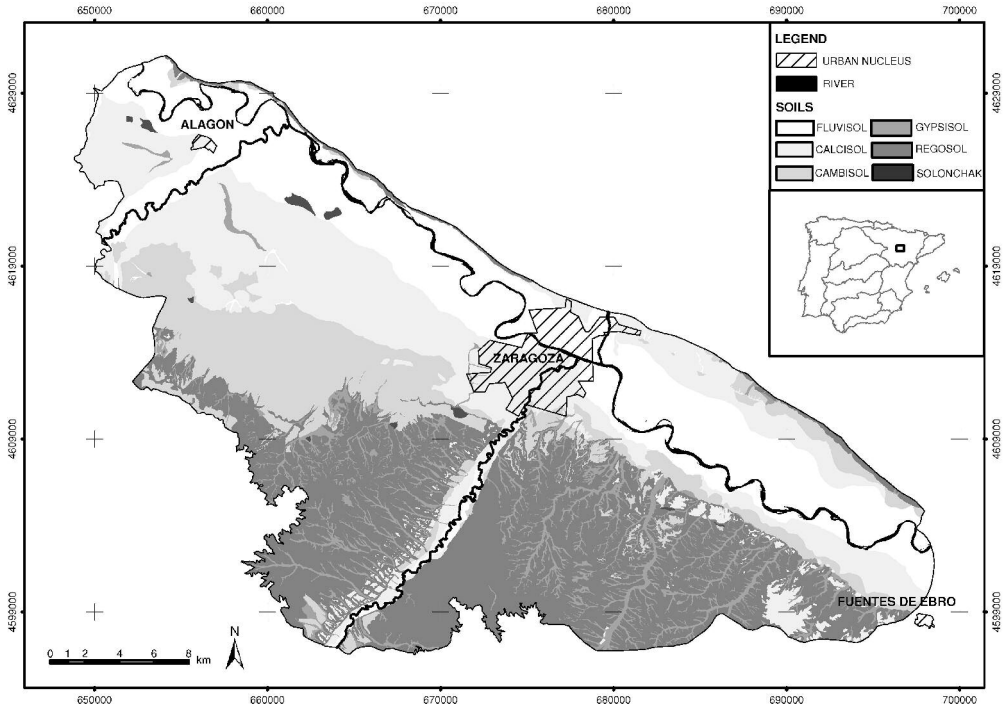

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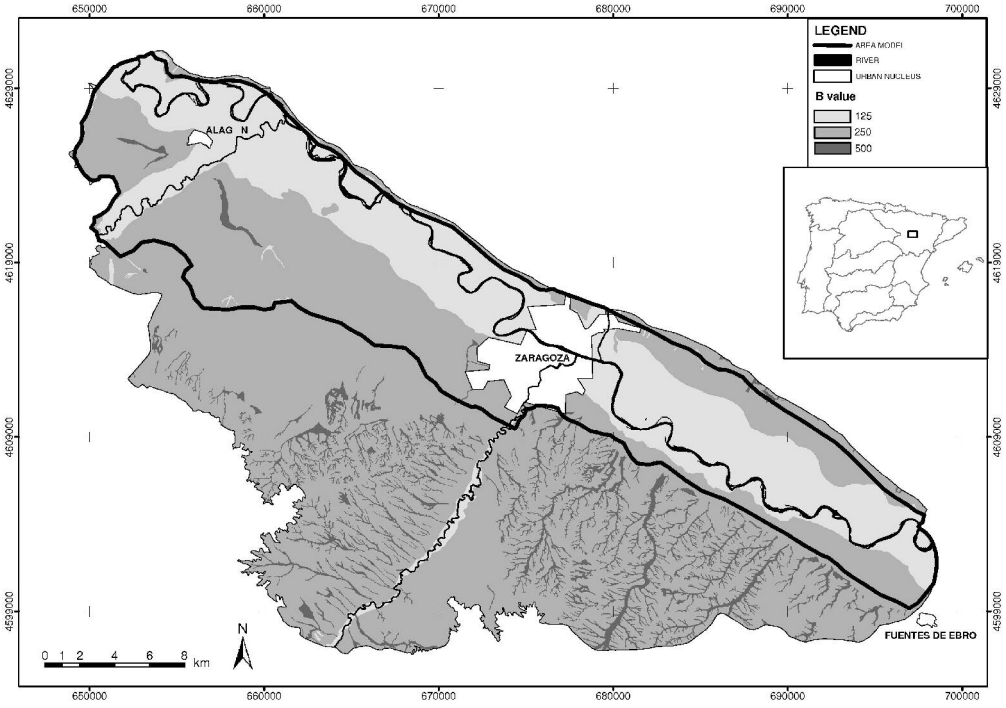

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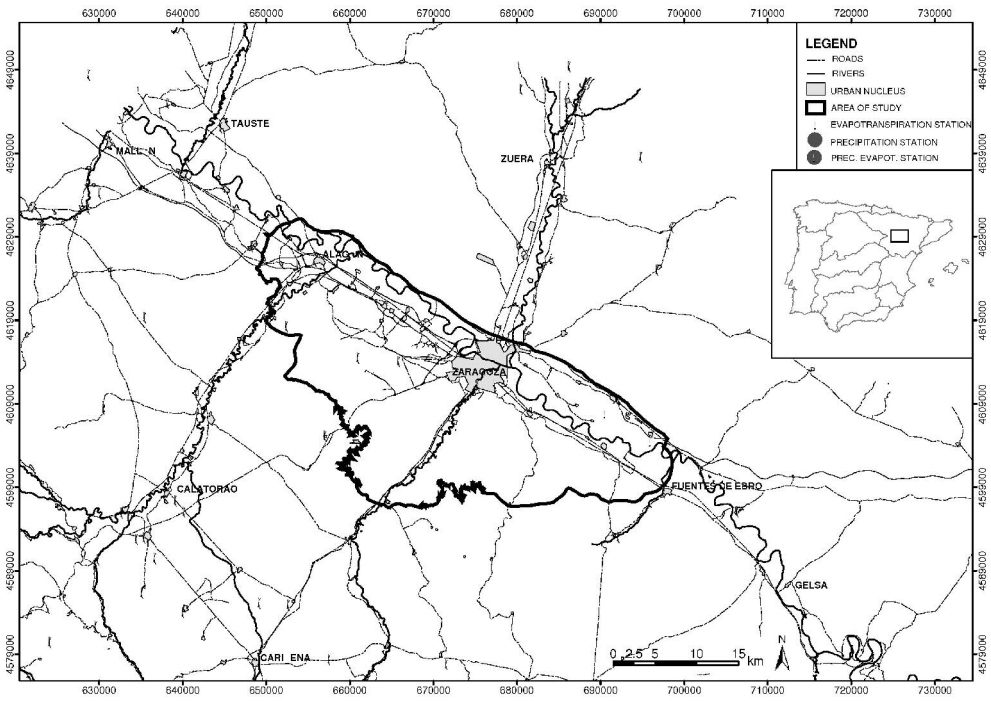

Figure 4: Map of the locations of meteorological stations.

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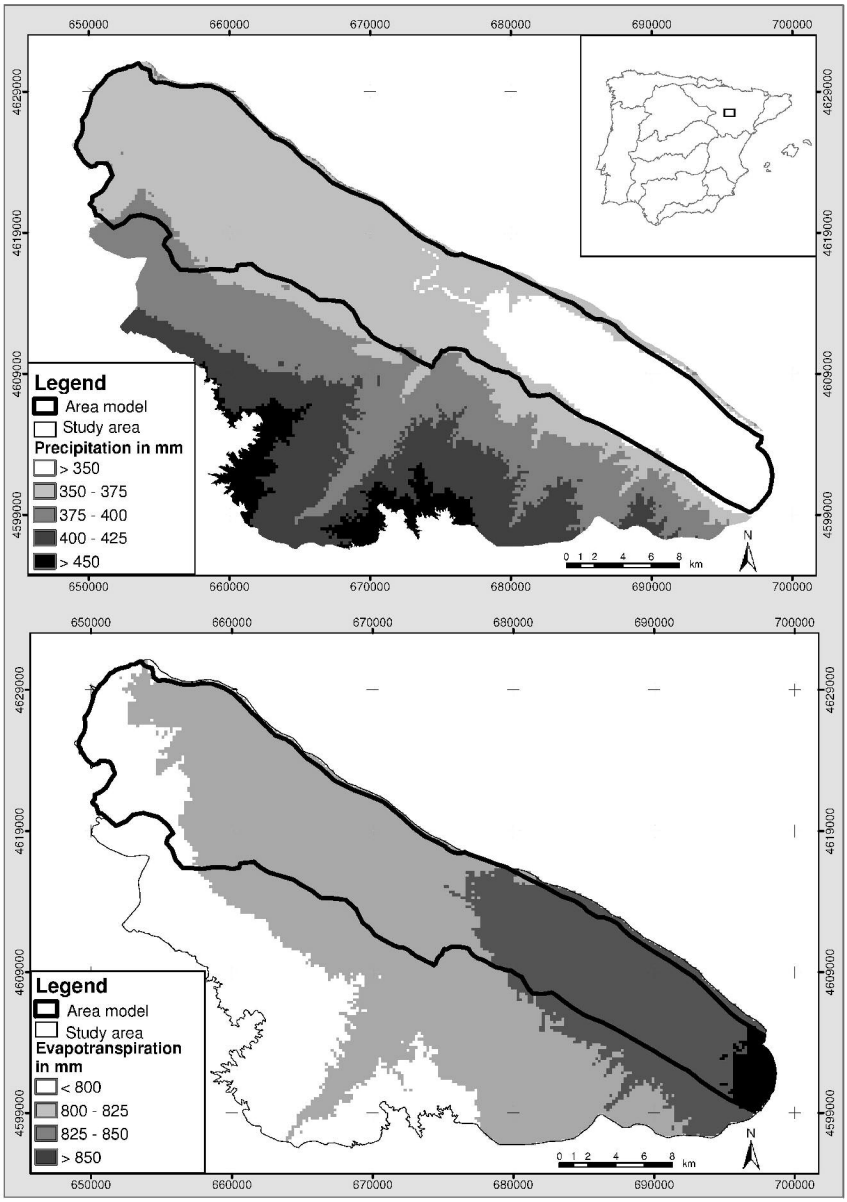

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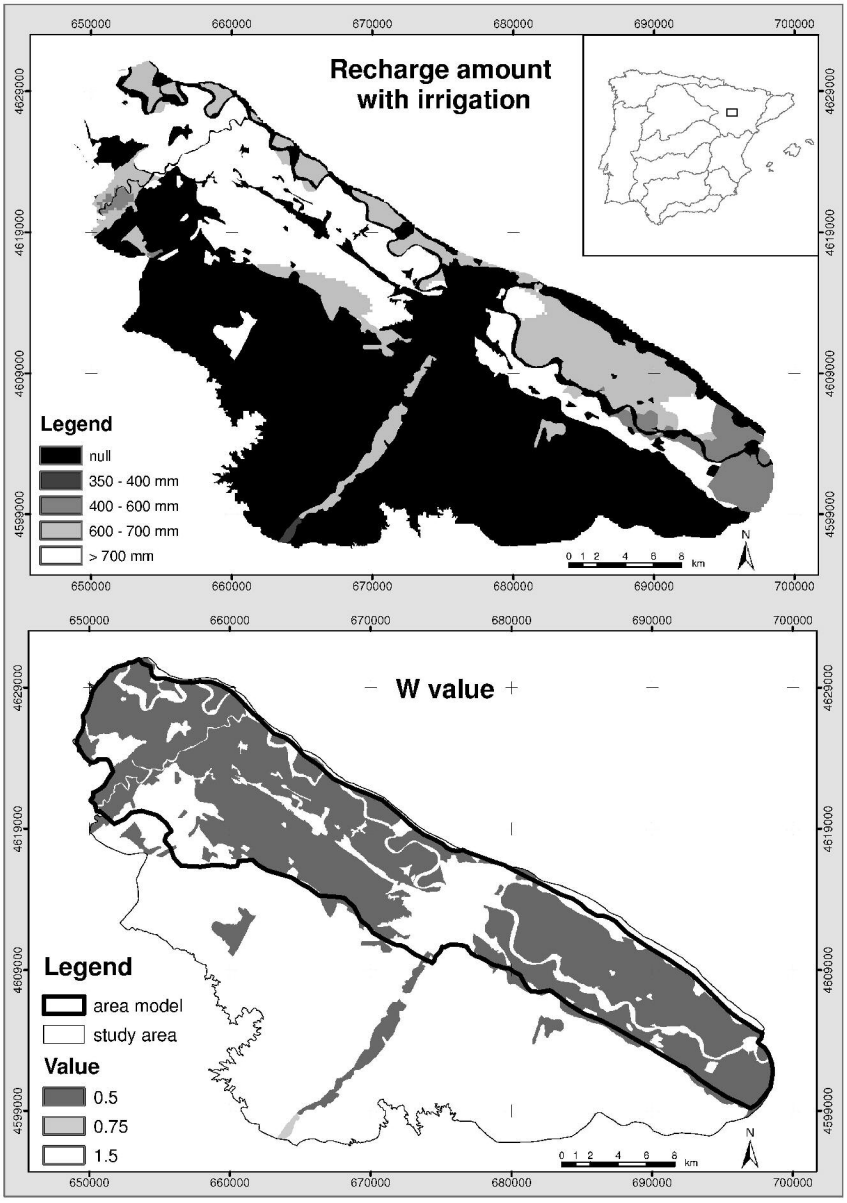

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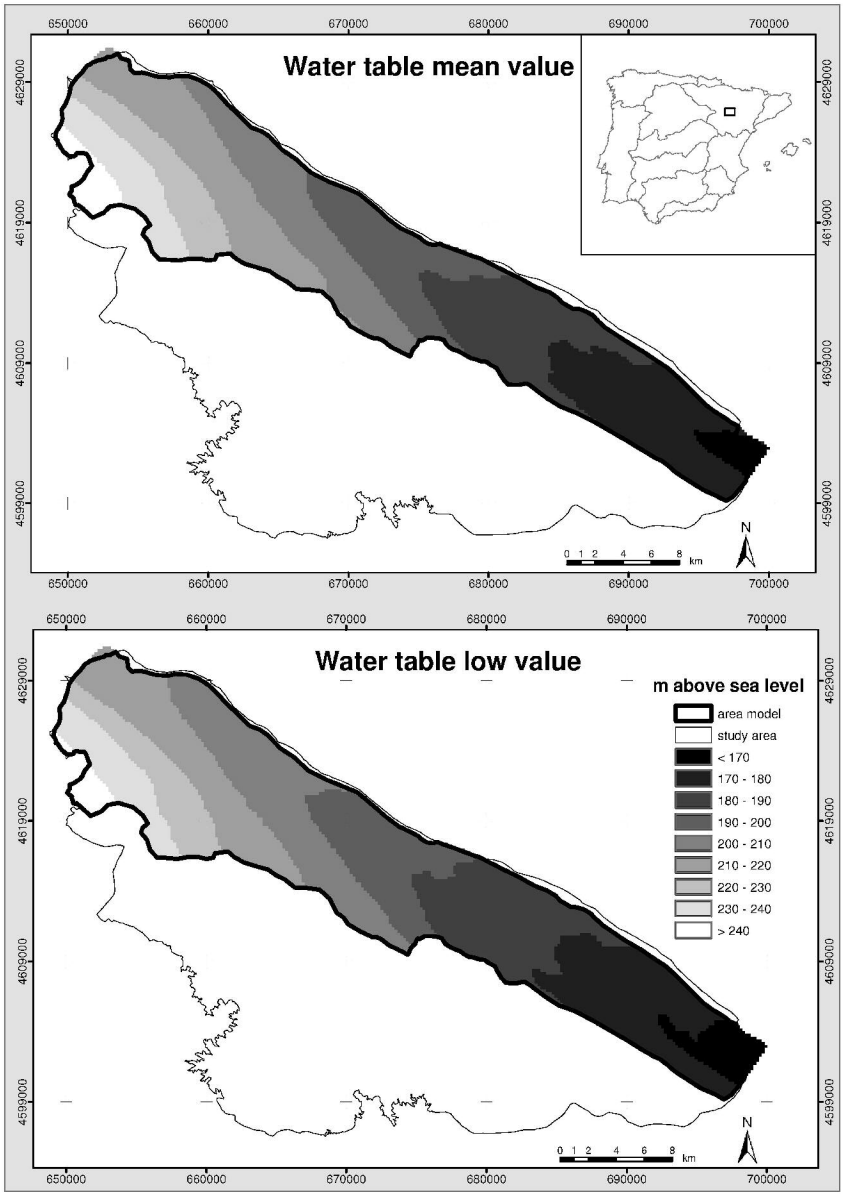

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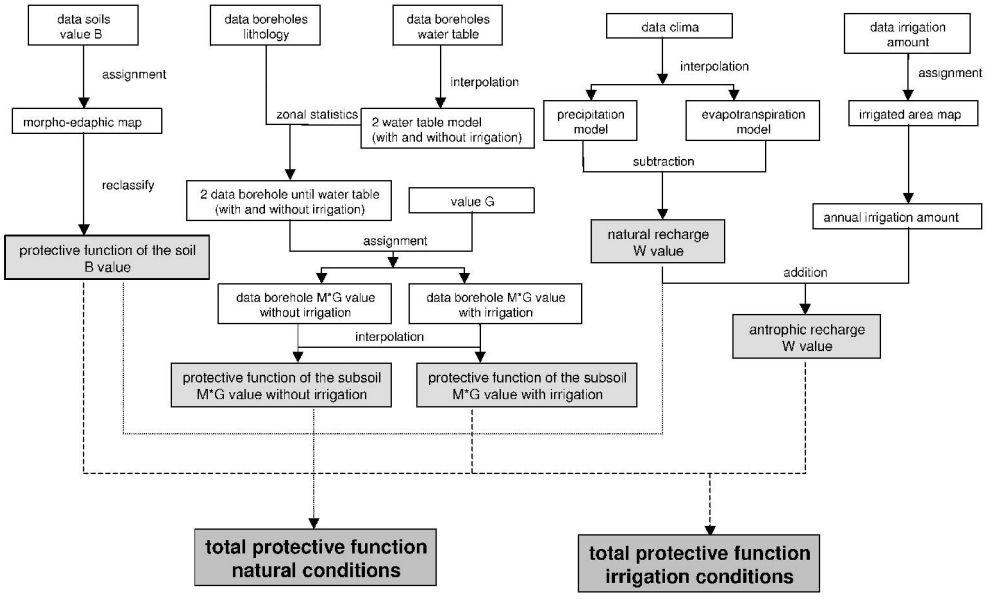

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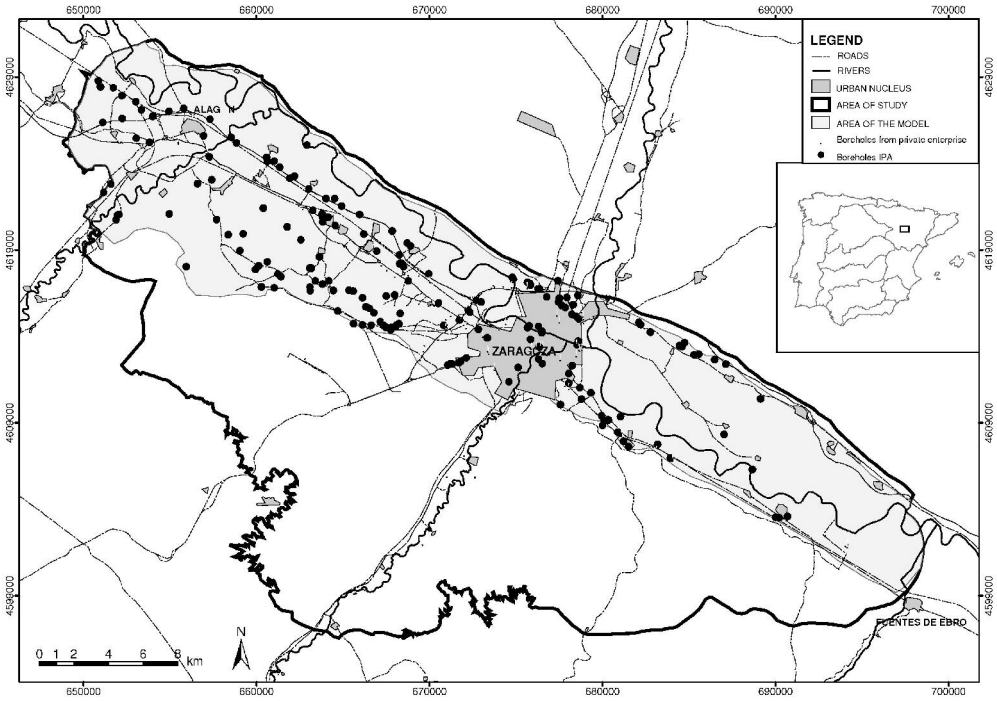

Figure 9: Location of the boreholes in the alluvial aquifer.

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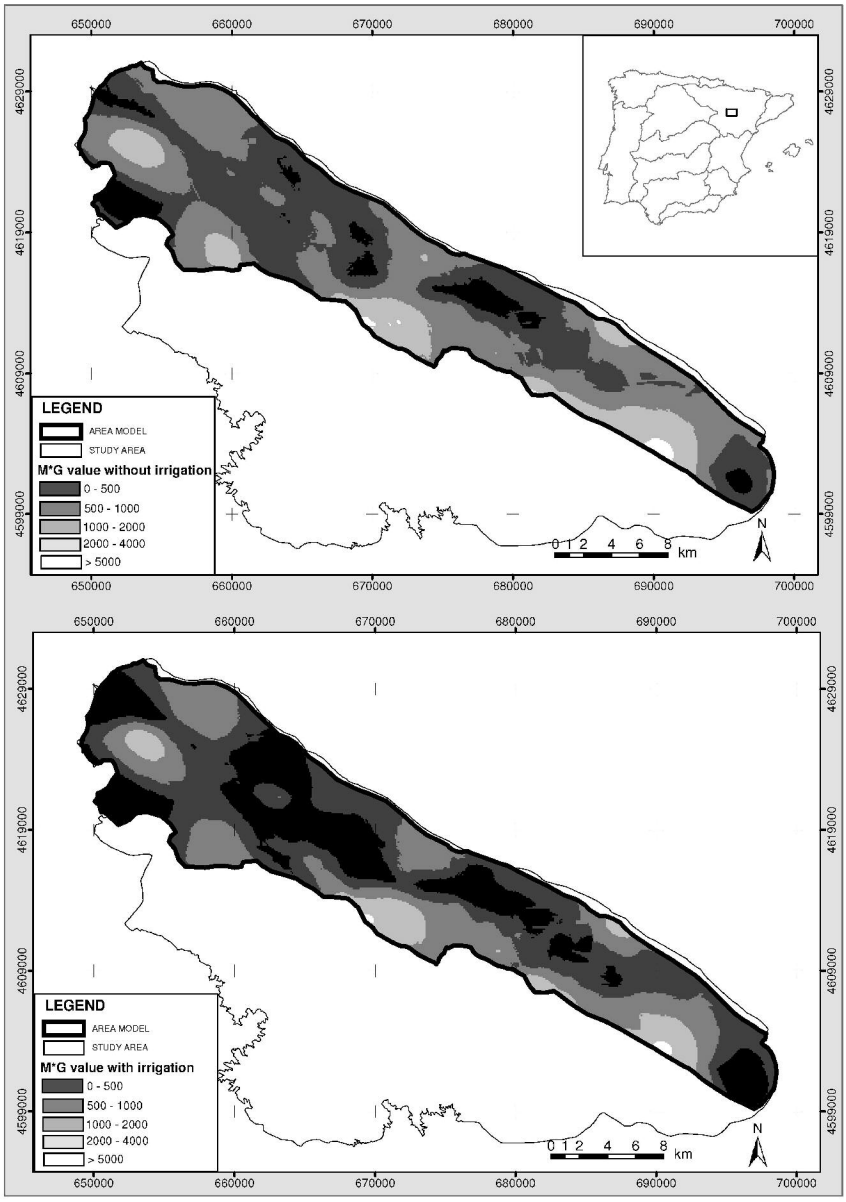

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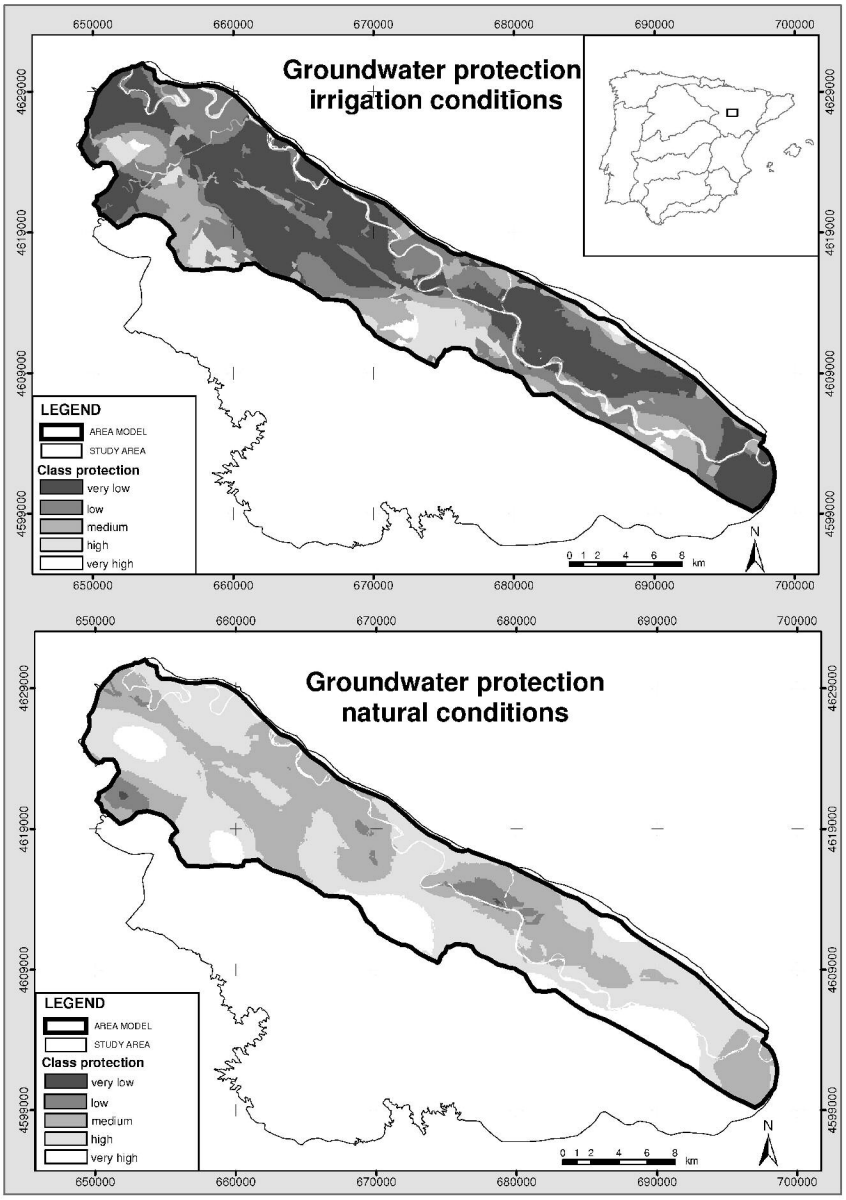
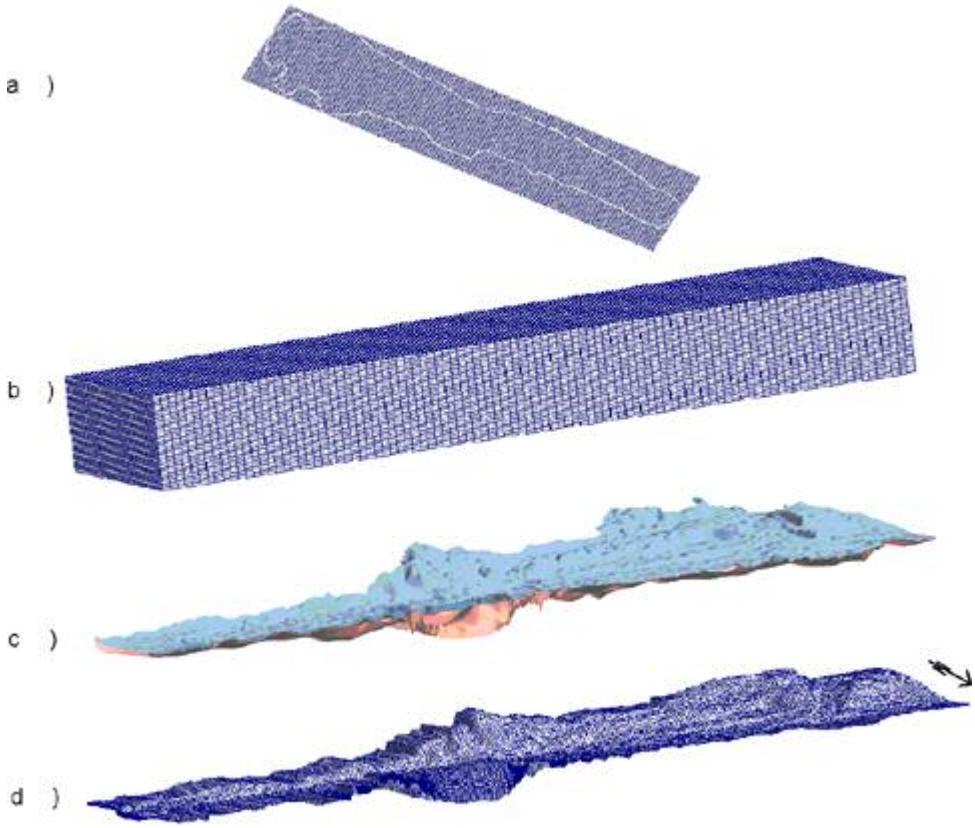


Figure 11: Groundwater vulnerability maps developed within ArcGIS.



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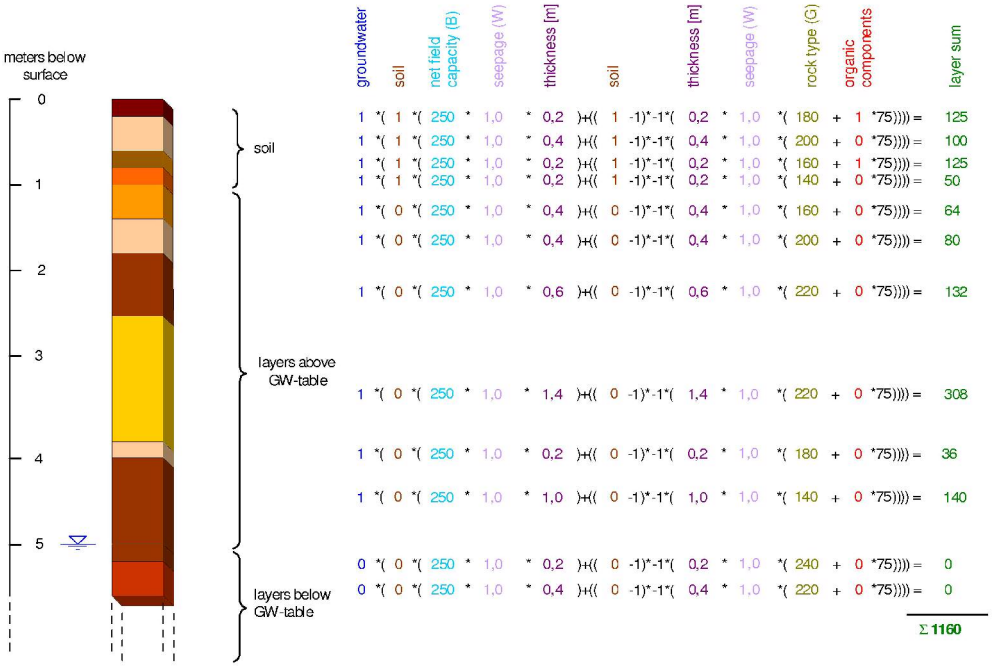

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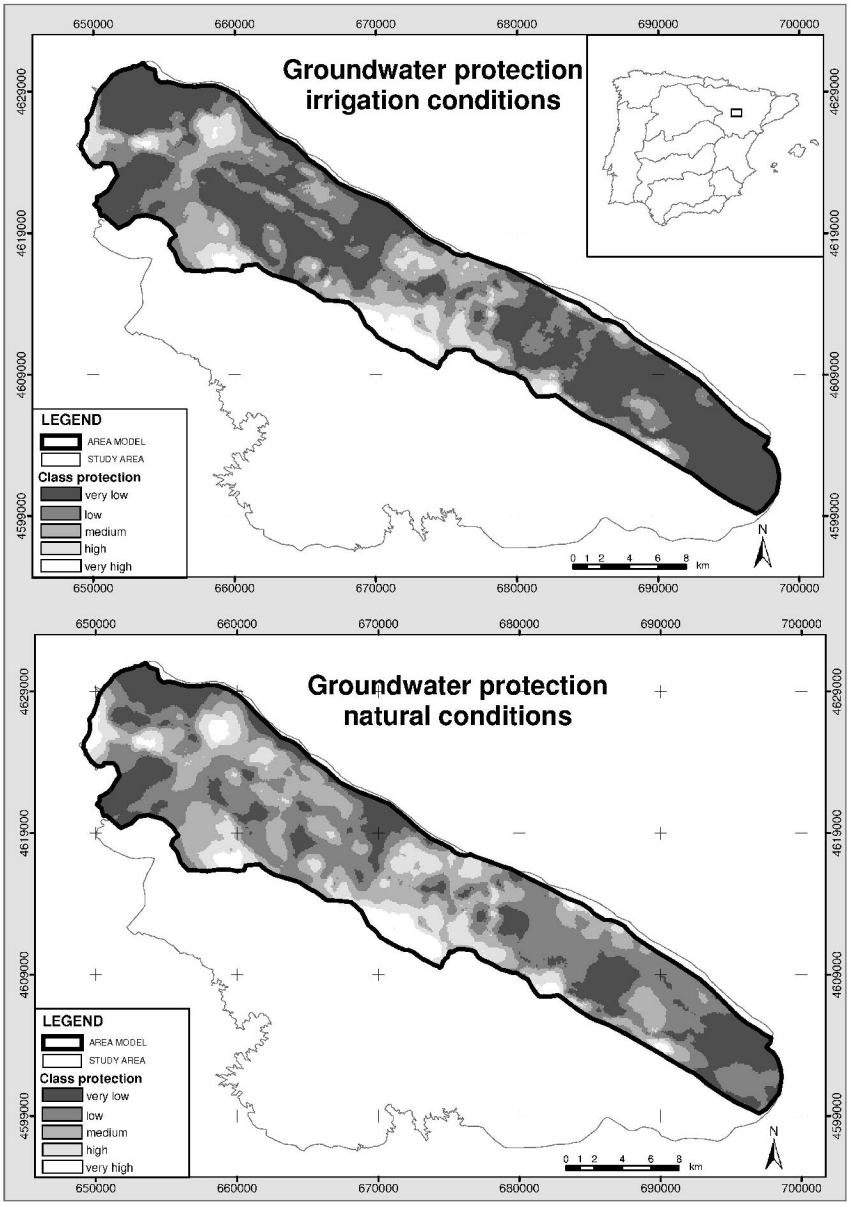

Figure 14: Groundwater vulnerability maps developed within Gocad.

Table 1: Classification of protective function total scores (after Holting et al., 1995).

Protective function	Total score
very high	> 4000
high	2000-4000
medium	1000-2000
low	500-1000
very low	< 500

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Table 2: B value for the different types of soil (after Hölting et al., 1995).

Soils/Properties	Effective field capacity mm/m	Hölting 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

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Table 3: G value according to Hölting et al. (1995) for different stratum description.

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

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.

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