Environ Geol (2006) 49: 653–673
DOI 10.1007/s00254-005-0104-1

ORIGINAL ARTICLE

Alexandra Gemitzi
Christos Petalas
Vassilios A. Tsihrintzis
Vassilios Pisinaras

Assessment of groundwater vulnerability to pollution: a combination of GIS, fuzzy logic and decision making techniques

Received: 28 August 2005
Accepted: 18 September 2005

A. Gemitzi
Department of Water Resources Management, Regional Authority of Eastern Macedonia Thrace, 69100 Komotini, Greece

C. Petalas · V. A. Tsihrintzis
V. Pisinaras · A. Gemitzi (✉)
Laboratory of Ecological Engineering and Technology, Department of Environmental Engineering, School of Engineering, Democritus University of Thrace, 67100 Xanthi, Greece
E-mail: agkemitz@env.duth.gr
Tel.: +30-25410-79393
Fax: +30-25410-79393

Abstract The assessment of groundwater vulnerability to pollution aims at highlighting areas at a high risk of being polluted. This study presents a methodology, to estimate the risk of an aquifer to be polluted from concentrated and/or dispersed sources, which applies an overlay and index method involving several parameters. The parameters are categorized into three factor groups: factor group 1 includes parameters relevant to the internal aquifer system's properties, thus determining the intrinsic aquifer vulnerability to pollution; factor group 2 comprises parameters relevant to the external stresses to the system, such as human activities and rainfall effects; factor group 3 incorporates specific geological settings, such as the presence of geothermal fields or salt intrusion zones, into the computation process. Geographical information systems have been used for data acquisition and processing, coupled with a multicriteria evaluation technique enhanced with fuzzy factor standardization. Moreover, besides assigning weights to factors, a second set of weights, i.e., order weights, has been applied to factors on a pixel by pixel basis, thus allowing control of the level of risk in the vulnerability determination and the enhancement of local site characteristics. Individual analysis of each factor group resulted in three intermediate groundwater vulnerability to pollution maps, which were combined in order to produce the final composite groundwater vulnerability map for the study area. The method has been applied in the region of Eastern Macedonia and Thrace (Northern Greece), an area of approximately 14,000 km^2. The methodology has been tested and calibrated against the measured nitrate concentration in wells, in the northwest part of the study area, providing results related to the aggregation and weighting procedure.

Keywords Groundwater vulnerability · Fuzzy logic Multicriteria evaluation · Geographic information systems

Introduction

Groundwater vulnerability assessment has been a challenging task, since it highlights areas where particular attention should be given to groundwater protection. The term groundwater vulnerability includes two basic parameters: intrinsic vulnerability and specific vulnerability (Gogu and Dassargues 2000). The former defines the vulnerability of groundwater to contaminants generated by human activities, taking into account only the inherent hydrogeological characteristics of the area, and is independent of the nature of the contaminants. The latter is specified for a particular contaminant or group of contaminants.

Untill now, several vulnerability assessment techniques have been developed. The most common ones are: the DRASTIC system (Aller et al. 1987), the GOD system (Foster 1987), the AVI rating system (Van Stempvoort et al. 1993), the SINTACS method (Civita 1994), the ISIS method (Civita and De Regibus 1995), the Irish perspective (Daly et al. 2002), the German method (Von Hoyer and Sofner 1998) and EPIK (Doerfliger et al. 1999). A comparison of the above aquifer vulnerability assessment techniques has been performed by Gogu and Dassargues (2000) and Gogu et al. (2003), which showed that there is a wide range in the results provided by each method and that, in many cases, there was disagreement. The reason for this is that aquifer vulnerability is not a measurable quantity, making the choice among the several methods quite an ambiguous task. In recent studies (Dixon et al. 2002; Dixon 2005), however, it was attempted to compare the results of vulnerability assessment methods with aquifer water quality data and perform a method sensitivity analysis.

This study presents a method of assessing aquifer vulnerability to pollution, at the regional scale, which takes into account the intrinsic hydraulic parameters of the aquifer and socioeconomic parameters, such as population distribution and concentration of the main industrial or other contaminant producing activities (e.g., landfill sites, salt works, oil industry, airports, ports, highways, etc.). Moreover, parameters such as the presence of geothermal fields or saltwater intrusion areas are introduced in the computation process, enriching the method with factors that take into account the particular characteristics of local aquifers and integrating them into regional scale calculations.

The method has been applied to the region of Eastern Macedonia and Thrace in Northern Greece (Fig. 1). The area is quite extensive, approximately totaling 14,000 km^2. All types of aquifers are present in the study area, i.e., confined, unconfined, karst and fractured aquifers. The process is not concentrated on any particular aquifer type, unlike other methods, such as EPIK (Doerflinger and Zwahlen 1998), which is developed especially for karst aquifers (Gogu and Dassargues 2000). A variety of activities, such as agricultural, industrial and urban land uses, exist in the area, thus exposing the aquifers to a wide range of contaminants.

Geographical information systems (GIS) combined with fuzzy logic and multicriteria evaluation techniques were used for data acquisition and the production of factor images, which served as map layers in the assignment process. The process involves transformation of the different ratings of the factor images into comparable values and aggregation of the individual factor scores, in order to create the intermediate and final groundwater vulnerability map.

The aggregation procedure includes factor distinction in three groups and the assignment of factor weights in

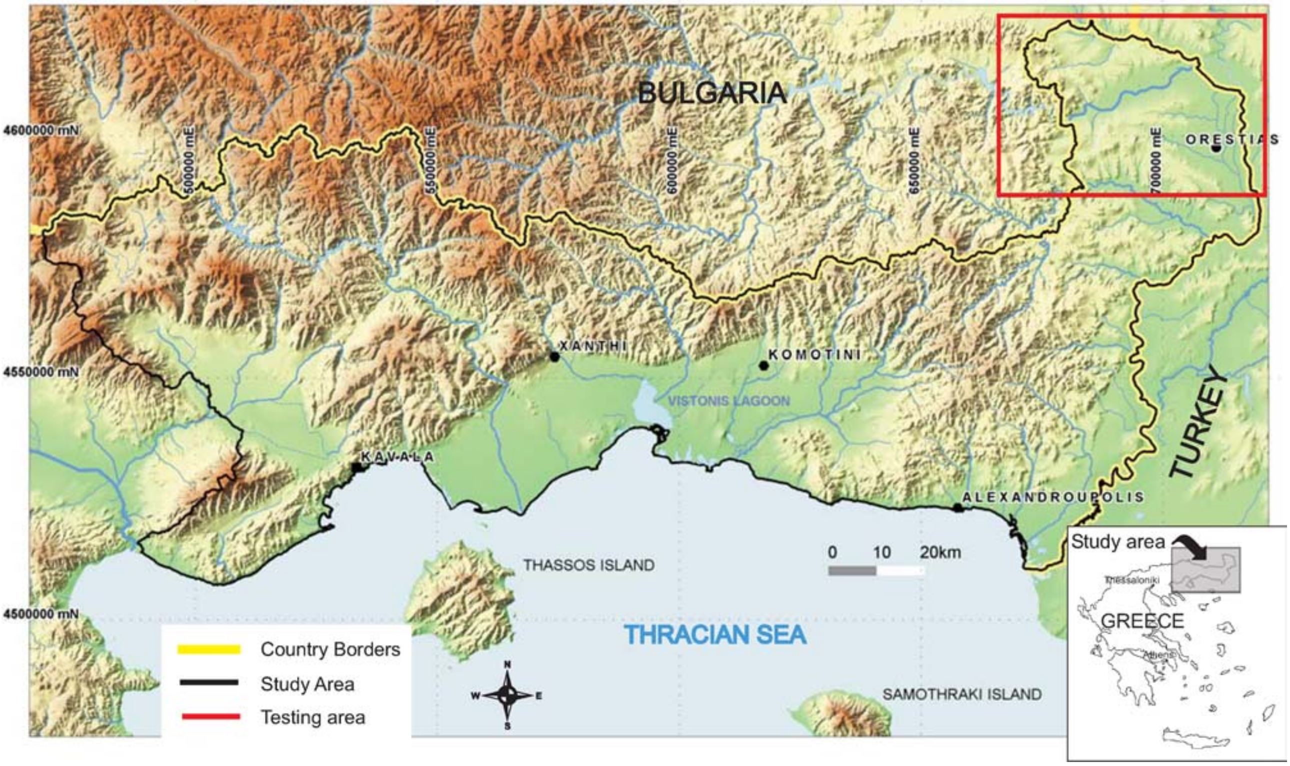


Fig. 1 Location map of the study area

each group separately, following the analytical hierarchy process (AHP) (Saaty 1977). A step beyond the typical AHP is the assignment in the present study, of a second set of weights known as order weights, which are applied on a per pixel basis for different rank-order positions of factors at every location (pixel) (Eastman 2003), thus modifying the degree to which factor weights influence the aggregation procedure. The application of the ordered weighted averaging technique has been presented by Eastman (2003), using a hypothetical site selection process. In this study, a first attempt has been made to apply this relatively new and experimental technique to a real case.

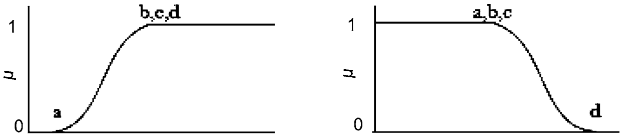
For each one of the three factor groups an intermediate aquifer vulnerability map was created; these maps were then combined in two ways in order to produce a composite aquifer vulnerability map. In order to calibrate and check the validity of the presented methodology, the results were compared to the measured nitrate concentration in wells in the northeast part of the study area (Fig. 1). This comparison reduces the subjectivity of the methodology and makes it very promising.

Methodology description

In the present study an overlay and index method of assigning groundwater vulnerability to pollution is presented. The study area has been discretized using a grid cell size of 60 m×60 m. Initially all the factors were standardized to a byte-level range of 0–255, which provides the maximum differentiation possible while analyzing data in byte type, thus requiring half the disk space needed for the normal two-byte integer files (Eastman 2003). Zero is assigned to the least vulnerable areas and 255 to the most vulnerable ones, transforming the different measurement units of the factor images, which served as GIS map layers, into comparable values using fuzzy membership functions. In this process, sigmoidal ("s-shaped") fuzzy membership functions, specified for each factor, are used, i.e., monotonically increasing and monotonically decreasing. The sigmoidal membership function is perhaps the most commonly used function in fuzzy set theory (Eastman 2003), offering a gradual variation from non-membership, i.e., 0, to complete membership, i.e., 1. The sigmoidal membership function can be specified by four parameters (a, membership rises above 0; *b*, membership becomes 1; *c*, membership falls below 1; *d*, membership becomes 0) (Fig. 2). It is expressed as:

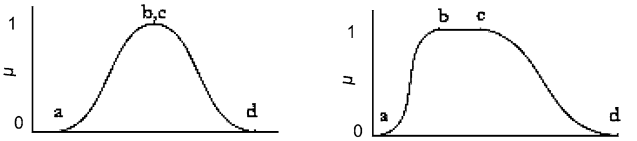
$$\mu(x) = \cos^2 a, \tag{1}$$

where, in the case of a monotonically decreasing function,



Monotonically increasing sigmoidal fuzzy membership function

Monotonically decreasing sigmoidal fuzzy membership function



Symmetric sigmoidal fuzzy membership function

Symmetric sigmoidal fuzzy membership function

Fig. 2 Sigmoidal fuzzy membership functions

$$a = \frac{x-c}{d-c}\frac{\pi}{2}, \tag{1a}$$

when $x < c$, $\mu(x) = 1$. In the case of a monotonically increasing function,

$$\alpha = \frac{1-(x-\mathrm{a})}{b-\mathrm{a}} \cdot \frac{\pi}{2} \tag{1b}$$

when $x > \mathrm{b}$, $\mu(x) = 1$.

Twelve factors are involved in the computation process, distinguished in three main groups according to the way they influence groundwater vulnerability to pollution. More specifically, the following 12 factors were introduced into the computation process of aquifer vulnerability: (1) aquifer type; (2) depth to water table; (3) hydraulic conductivity; (4) surface runoff; (5) land uses (non-point source pollution); (6) concentrated polluting activities (point source pollution); (7) proximity to rivers; (8) proximity to highways; (9) proximity to residential areas; (10) presence of environmentally protected areas; (11) presence of geothermal fields; and (12) presence of saltwater intrusion zones. The first group includes factors 1–3, relevant to the hydraulic properties of the aquifer, which are not dependent on external stresses; thus characterizing the intrinsic vulnerability of the aquifer. The second group comprises factors 4–10, relevant to the socioeconomic and development status of the study area, reflecting the impact of external anthropogenic forces on the aquifer system; thus describing the specific aquifer vulnerability. In this second group, a factor that describes surface runoff accumulation is also included, as it is considered an external parameter to the aquifer system. The third group includes factors 11 and 12, which are relevant to the presence of particular geological conditions, such as areas influenced by saltwater intrusion or those including geothermal fields. In the present study, these three distinct categories were examined separately, producing three types of intermediate aquifer vulnerability to pollution maps.

In each group, the factor weights were assigned according to how important each factor was. To make the process of assigning factor weights more objective, a pairwise comparison was applied in which only two criteria were considered at a time. That way it is more likely to produce a more robust set of criteria weights (Eastman 2003). The implemented technique of the pairwise comparison of factors was developed by Saaty (1977) in the context of a decision-making process known as the AHP (Pavlikakis and Tsihrintzis 2003). In the procedure for multicriteria evaluation in the present study, using a weighted linear combination, it was necessary that the assigned factor weights sum to one. In Saaty's (1977) technique, factor weights can be derived by taking the principal eigenvector of a square reciprocal matrix of pairwise comparisons between the criteria. The comparisons concern the relative importance of the two criteria involved in determining suitability for the stated objective (Eastman 2003). An index of consistency, known as the consistency ratio (CR) (Saaty 1977), can be produced, since the complete pairwise comparison matrix contains multiple paths by which the relative importance of criteria can be assessed, thus, determining the degree of consistency that has been used in developing the ratings. The CR presents the probability that the matrix ratings are randomly generated (Saaty 1977) and indicates that matrices with CR ratings greater than 0.10 should be re-evaluated. In addition to the overall CR, it is also possible to analyze the matrix to determine where the inconsistencies arise (Eastman 2003).

Additionally, in the present study, one more set of weights, i.e., order weights, has been applied to each group of factors analyzed, following a procedure known as the ordered weighted average (Eastman 2003). Order weights are quite different from factor weights. They do not apply to any specific factor. Instead, they are applied, on a pixel-by-pixel basis, to factor scores as determined by their rank ordering across factors at each location (pixel). Order weight 1 is assigned to the lowest-ranked factor for that pixel (i.e., the factor with the lowest score), order weight 2 to the next higher-ranked factor for that pixel, and so forth. In that way, a single order weight can be applied to pixels from any of the various factors depending upon their relative rank order. This procedure offers the possibility to adjust computations, according to how risky or strict the decision is desired to be, i.e., whether pixel values are stressed toward the lower or higher vulnerability values. Taking as an example factor group 1, including factors related to the intrinsic aquifer vulnerability, i.e., aquifer type, hydraulic conductivity and depth to water table, the assignment of order weights could have the results shown in Table 1.

In the first case, the weight is distributed evenly among all factors, regardless of their rank order position. The result is exactly in the middle, in terms of risk. In the second case, the factor with the lowest score, i.e., the less vulnerable, receives all the weight, regardless of the factor weights assigned. This result incorporates a high level of risk, as all the pixels in the study area are assigned the value of the lowest vulnerability factor. The intermediate groundwater vulnerability map produced that way is more likely to have underestimated values of groundwater vulnerability since it is assigned values from the factor with the lowest score. On the contrary, the third case assigns all weight to the factor with the highest score in each pixel, resulting in pixel values equal to the highest vulnerability factor. This is the most conservative case, as the values assigned in the vulnerability map are taken from the factor with the highest vulnerability score. In that way extensive areas are assigned overestimated values of groundwater vulnerability to pollution, leading to a risk averse decision in the groundwater protection scheme, demonstrating, though, no trade-off. The skewing of order weights, toward either factor with the lowest or highest score, results in all possible cases between risk and stringency.

In order to apply the above described methodology, all factors were introduced as map layers in the GIS program MapInfo Professional ver. 7.8. Raster data were processed with Vertical Mapper ver. 3.1, whereas fuzzy factor standardization and the multicriteria evaluation has been performed using the GIS program Idrisi Kilimanjaro.

Table 1 Example of order weight assignment

Factors	Aquifer type	Hydraulic conductivity	Depth to water table
Moderate level of risk—moderately strict decision			
Order weights	0.33	0.33	0.33
Rank	1st	2nd	3rd
High level of risk—no strict decision			
Order weights	1	0	0
Rank	1st	2nd	3rd
Low level of risk—very strict decision			
Order weights	0	0	1
Rank	1st	2nd	3rd

Methodology application

Factor group 1: assignment of intrinsic aquifer vulnerability

As mentioned earlier, factor group 1 comprises factors related to intrinsic aquifer characteristics, i.e., aquifer type, hydraulic conductivity and depth to water table (Fig. 3).

Factor 1: aquifer type

Four discrete categories of aquifer types were assigned in the study area, i.e., unconfined aquifer, confined aquifer, karst (limestone), and fractured aquifers (groundwater in igneous and metamorphic rocks) (Fig. 3a). While most factors can be automatically rescaled using some mathematical function, rescaling categorical data such as aquifer types requires giving a rating to each category based on some knowledge, according to their relative vulnerability to pollution. In this case, the aquifer vulnerability rating is specified assuming that the most vulnerable ones are karst aquifers, which received the highest rating value, i.e., 255. Unconfined aquifers are the next most vulnerable, which received a value of 155. Confined aquifers were assigned a value of 75 whereas fractured aquifers are treated as the least vulnerable ones, receiving a value of 0. Karst aquifers comprise karstified limestones and marbles of various ages, from the middle Mesozoic to the Eocene. Karstification results in high hydraulic conductivity values and, consequently, vulnerability to pollution is particularly high. Karst aquifers occupy 13.3% of the study area (1,808 km^2). Unconfined aquifers are pore aquifers, mainly including the most recent alluvial deposits of the Quaternary to the upper Miocene age. Since they are not protected by a confining layer, any potential pollutant released on the ground surface may easily reach the groundwater. Thus, unconfined aquifers are considered as the second most vulnerable to pollution. They form 25.2% of the study area, i.e., 3,427 km^2. Confined aquifers are protected by a confining layer, so pollutants are not expected to easily reach groundwater. They comprise mainly sedimentary and metasedimentary formations of the late Mesozoic to the Pliocene age, with an aerial extent of 1,863 km^2 (13.7% of the study area). The least vulnerable aquifers are the fractured ones, which cannot be considered as ordinary aquifers in the sense that they are not water bearing formations. They only carry water through fractures and faults due to tectonic events. In the study area, geological formations that include fractured aquifers occupy 47.8% of the study area (6,500 km^2), are located mainly in the northern mountainous part and are considered as old rock formations, forming part of the Hellenic hinterland of the Palaeozoic or even older age. The rock types forming these faulted aquifers are gneiss, amphibolites, leptinites, granodiorites, marbles, migmatites, metabasites, and ultrabasites. Since they have been affected by pre-alpine tectonics as well as by alpine deformation during tertiary times, they appear to be faulted and fractured.

Factor 2: hydraulic conductivity

A well inventory has been created including over 2,000 boreholes in the study area. Data have been collected from a variety of sources, such as the Greek Geological Survey (Vergis 2000; Dimadis et al. 2001; Papadopoulos et al. 2001; Papadopoulos and Romaidis 2002) and Democritus University of Thrace, as well as from individual drillers and various previous studies (Diamantis 1993; Petalas 1997; Panilas 1998; Pliakas et al. 1999; Petalas et al. 2001). In almost 50 boreholes, pumping tests were performed and the hydraulic properties of the corresponding aquifers were calculated. In areas where no data exist, hydraulic conductivity values were assigned based on bibliographical evidence (Fetter 1994), type of geological formation, grain size and the degree of consolidation. Typical hydraulic conductivity values are: 10^{-7}–10^{-9} m/s for metamorphic rocks (i.e., gneiss, schists, migmatites, metabasites, amphibolites, and non-karstified marbles), 10^{-8}–10^{-7} m/s for clays and marls, 10^{-6} m/s for flysch formations, 10^{-5}–10^{-3} m/s for sands, according to their fine grain content, 10^{-2}–10^{-3} m/s for gravels and conglomerates, and 10^{-2}–10^{-1} m/s to karstified marbles and limestones (Fig. 3b). A monotonically decreasing sigmoidal fuzzy membership function was applied in order to transform the above hydraulic conductivity values to a continuous set of values ranging from 0 to 255. The control points were 10^{-1}, where function membership becomes 1 (i.e., at highest groundwater vulnerability) and 10^{-9}, where function membership becomes 0 (i.e. at lowest groundwater vulnerability).

Factor 3: depth to water table

Depth to water table has been assigned using the well inventory discussed in the previous section. Moreover, data from 168 springs were incorporated in the well inventory. The spring locations were assigned a zero depth to water table, whereas a negative value of depth to water table, i.e., −1, indicates areas where artesian aquifers overflow. A 500 m buffer zone was created around each borehole and spring, and the depth to water table for the whole zone was assigned as equal to the depth to water table of the associated point. In fractured aquifers, the depth to water table was assigned an arbitrary value of 100, as no groundwater level is present in these rock formations and, consequently, a relatively

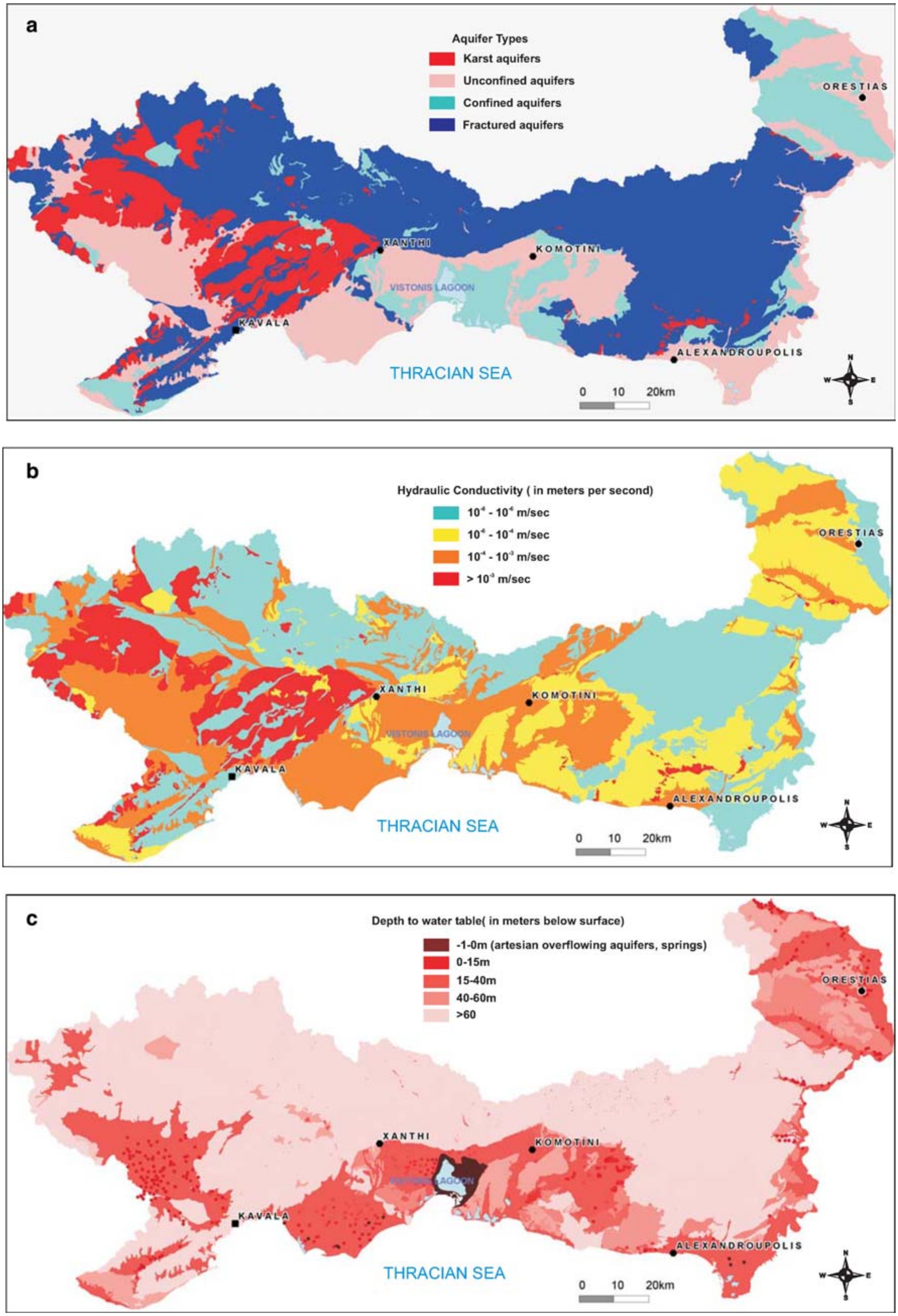


Fig. 3 Factors of the internal aquifer system properties

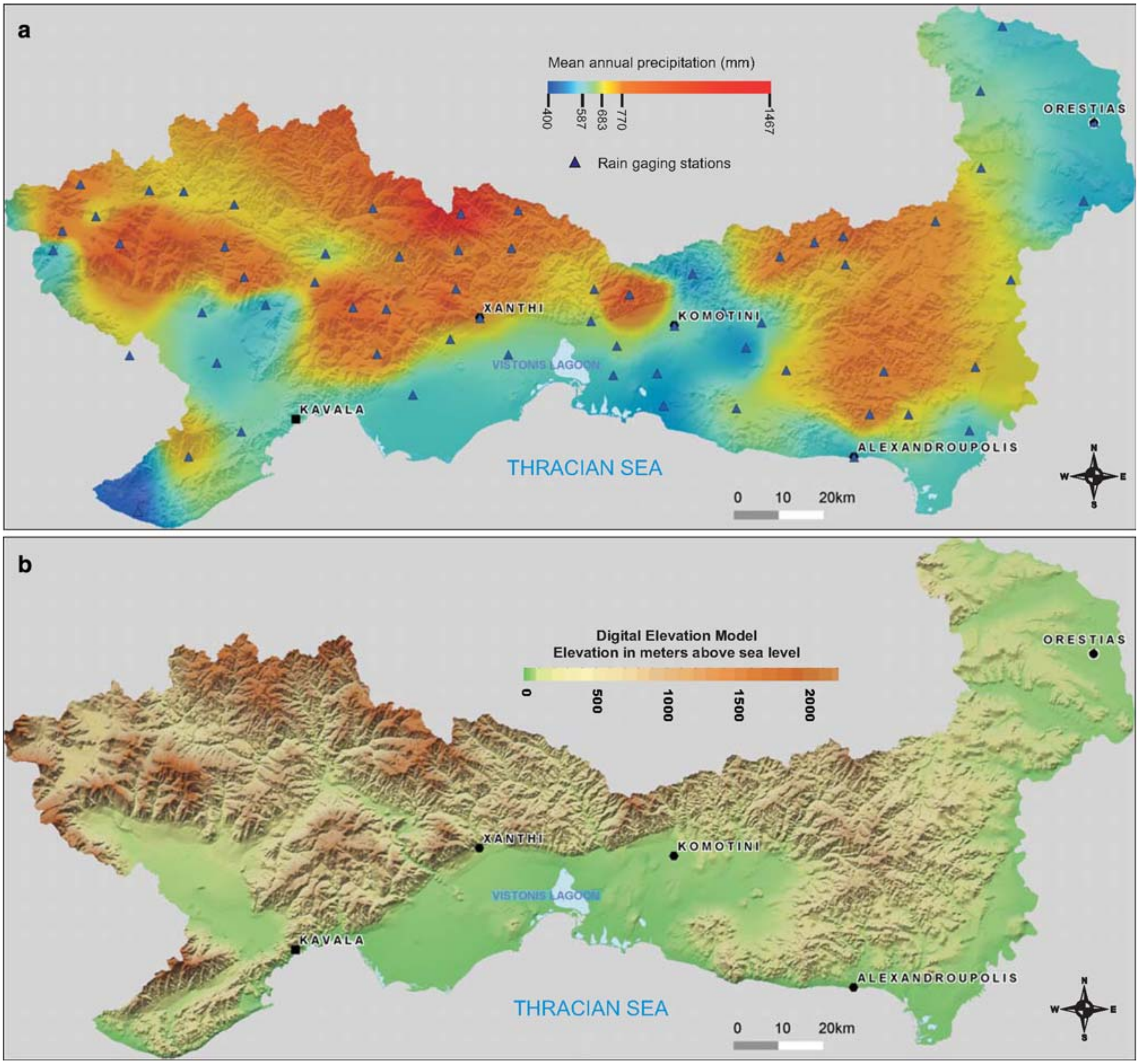


Fig. 4 **a** Precipitation distribution in the study area. **b** Digital elevation model. **c** Permeability of geological formations. **d** Surface runoff accumulation

high value for depth to water table is needed for calculations to proceed (Fig. 3c). A monotonically decreasing sigmoidal fuzzy membership function was applied in order to transform the above depth to water table values to a continuous set of values ranging from 0 to 255. The control points were 0, where function membership becomes 1 (i.e., at highest groundwater vulnerability) and 100, where function membership becomes 0 (i.e. at lowest groundwater vulnerability). Values greater than 100 receive the same function membership value of 0 since higher values of depth to water table were considered to have no more impact on groundwater vulnerability. In areas where overflowing occurs (i.e., artesian aquifers with their piezometric surface above the topographic surface) an arbitrary value of 25 (low vulnerability), in the scale of 0–255 has been assigned since, in this particular case, the water is flowing out of the aquifer, thus minimizing the potential of groundwater pollution in case a pollutant is released.

Factor group 2: assignment of aquifer vulnerability related to external forces

Factor group 2 comprises external factors to the aquifer system, i.e., surface runoff, non-concentrated land

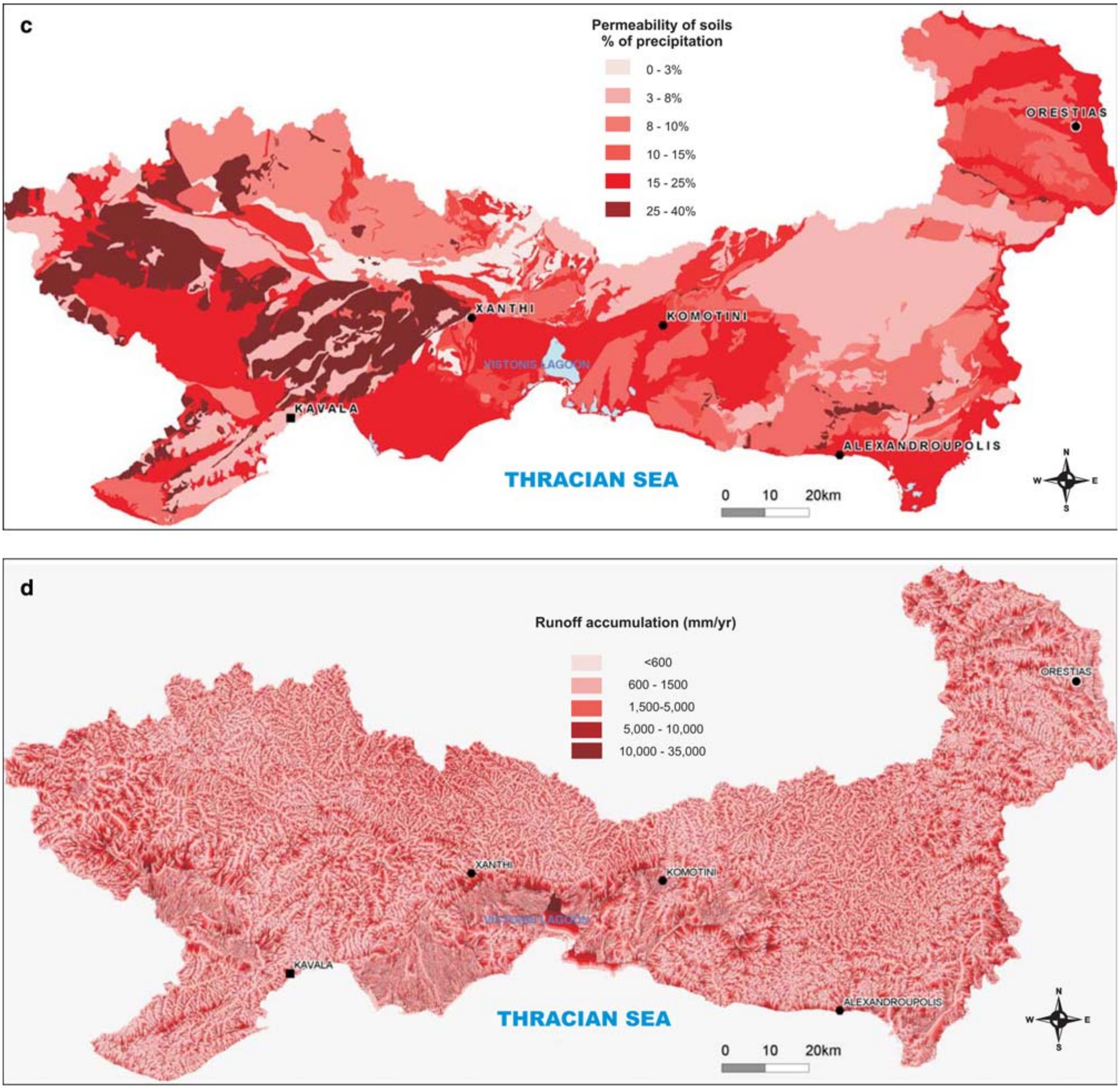


Fig. 4 (Contd.)

uses, proximity to concentrated land uses, proximity to major rivers, proximity to residential areas, areas protected by national law or international environmental treaties and proximity to highways and railways (Figs. 4, 5, 6, 7).

Factor 4: surface runoff

Each pixel in the study area receives an amount of rain (Fig. 4a). RUNOFF is a specially developed routine incorporated in the GIS program Idrisi Kilimanjaro that calculates the accumulation of rainfall units per pixel, based on an elevation image (DEM) (Eastman 2003) (Fig. 4b), and is a modification of the algorithm described by Jenson and Domingue (1998). The higher the accumulation of runoff in a pixel the more vulnerable the pixel is to groundwater pollution. A simple RUNOFF analysis accumulates rainfall on a per pixel basis as if one unit of rainfall was dropped on every location. In our case, the mean annual precipitation data from 82 gaging stations scattered all over the study area, for the time period 1966–2001, was incorporated in the routine. Besides providing a DEM, the routine has been enhanced with a permeability image (Fig. 4c), in order to

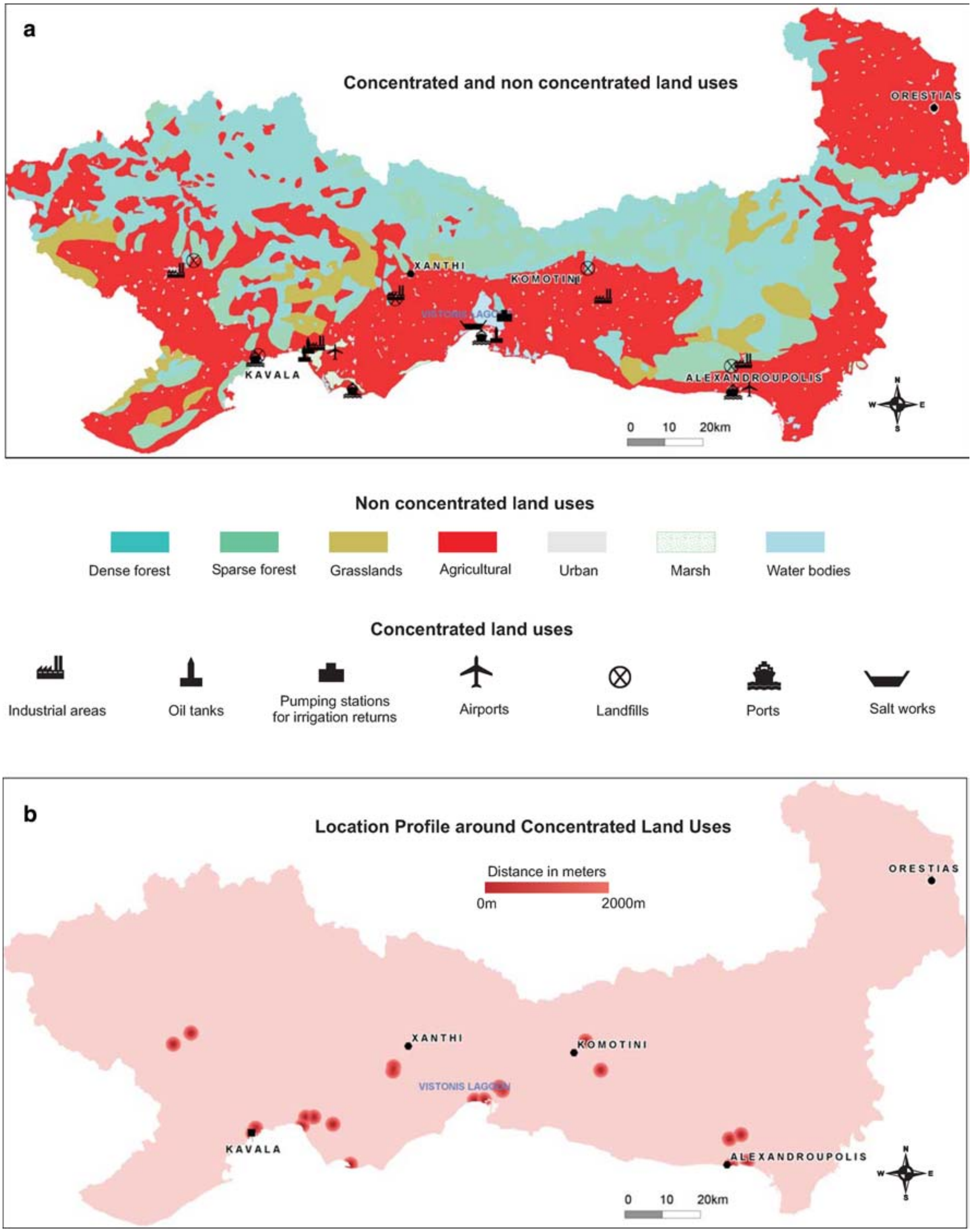


Fig. 5 **a** Concentrated and non-concentrated land uses. **b** Location profile around concentrated activities

account for soil permeability and accordingly adjust the accumulated rainfall (Fig. 4d) (Eastman 2003).

A monotonically increasing sigmoidal fuzzy membership function was applied to transform runoff accumulation to a 0–255 scale. The control points were 600, where function membership becomes 0, and 35,000 mm/year, where function membership becomes 1. The value of 35,000 mm/year, after multiplication by the pixel size, i.e., 3,600 m^2, corresponds to an average discharge of 345 m^3/day. The first and the

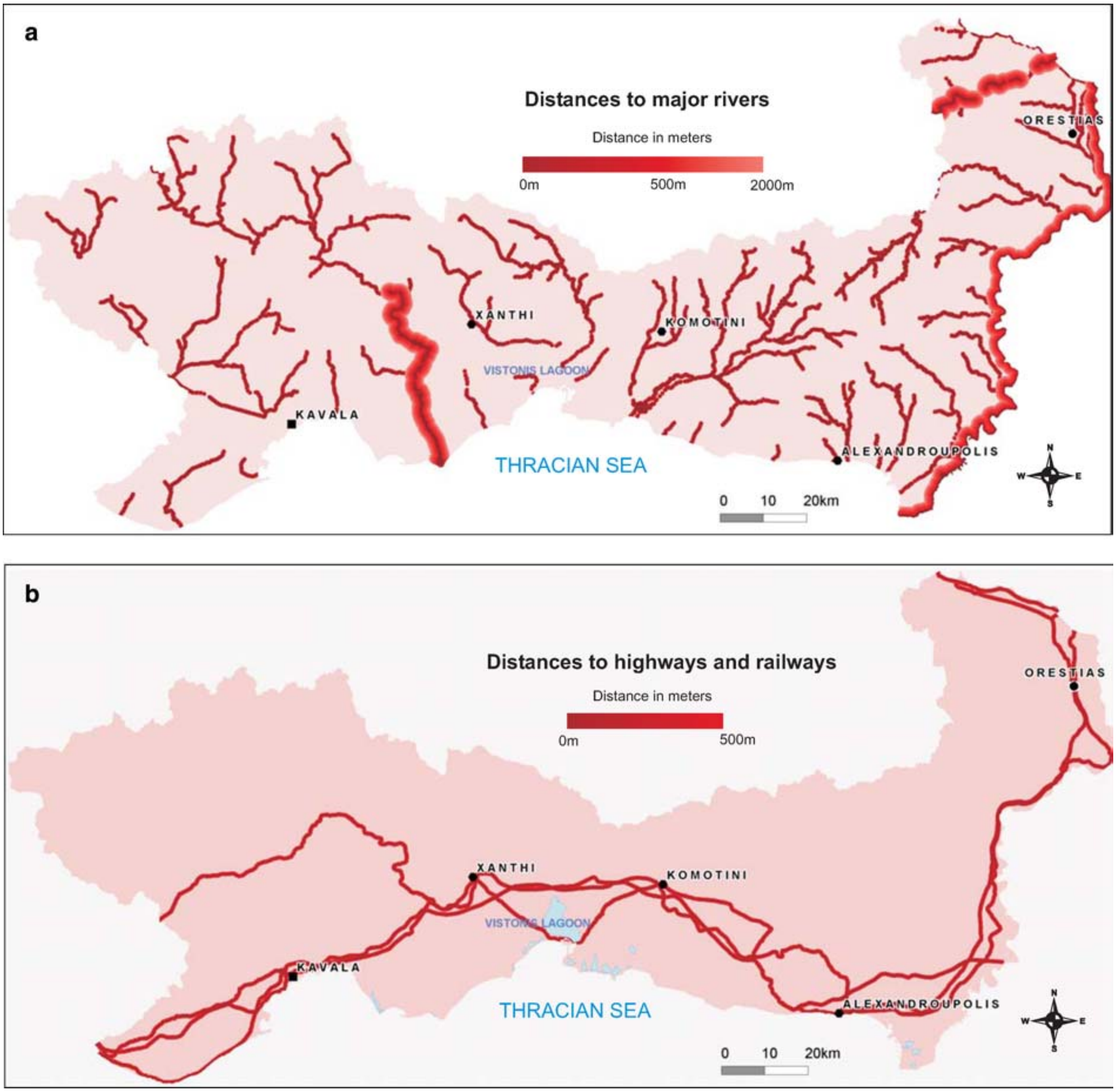


Fig. 6 Proximity to: (**a**) major rivers and (**b**) highways and railway in the study area

second control points were selected after imposing a quantiles classification scheme and placing an equal number of pixels into each class. The end point of the first class, i.e., 600 mm/year (approximately 5% of the study area), and the starting point of the last class, i.e., 35,000 mm/year (basin outlets) (upper 5% of the study area), were defined as control points 1 and 2, respectively, for the sigmoidal fuzzy function. Pixels with accumulated runoff values lower than 600 mm/year and higher than 35,000 mm/year were considered equally vulnerable to the first and second control points and received a function membership value of 0 (lowest vulnerability) and 1 (highest vulnerability), respectively.

Factor 5: non-concentrated land uses

This factor includes all types of land uses that, unlike industrial land uses, cover a wide range of the study area. The following six discrete land use categories are introduced in the calculation process: dense forests, sparse forests, grasslands, water bodies, agricultural and urban (Fig. 5a). As in the case of aquifer type factor, rescaling categorical data such as land uses requires giving a rating to each category, based on some knowledge (Eastman 2003), according to their relative groundwater vulnerability. On the continuous 0–255 scale, a vulnerability rating of 255 has been assigned to agricultural and urban land uses, since they are consid-

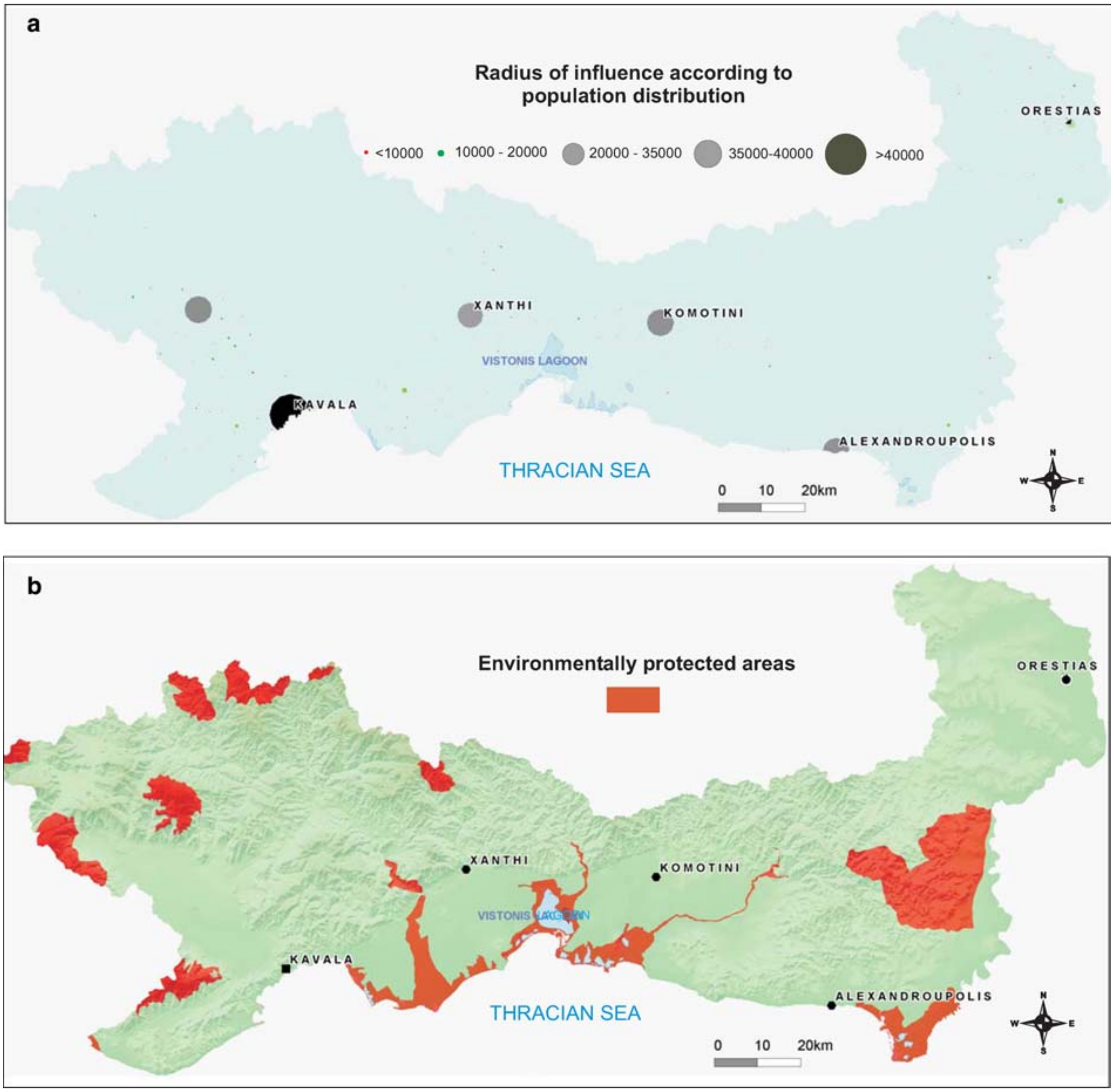


Fig. 7 **a** Radius of influence of residential areas according to population distribution. **b** Environmentally protected areas

ered to be equally polluting land uses, worse than any other non-concentrated human activity as far as groundwater pollution is concerned. A rating of 150 was assigned to the grasslands where most of the livestock farming takes place. A value of 30 has been assigned to sparse forests and 0 to dense forests and to water bodies (the least groundwater vulnerable areas as far as land uses are concerned).

Factor 6: proximity to concentrated land uses

Concentrated land uses include human activities, which may result in groundwater pollution if no protective measures are taken. The following major concentrated human activities are distinguished in the study area: landfills, industrial areas, airports, oil tanks, ports, salt works and pumping stations for irrigation returns (Fig. 5a). Facilities such as gas stations, septic tanks and wastewater treatment units are considered to be part of the urban net and are not examined within this factor. All the above activities are not supposed to have the same degree of vulnerability, i.e., landfill leachates are far more polluting than pumping stations for irrigation returns. An importance weight for each of the above activities has been assigned as follows: landfills 1,000; industrial areas 750; and ports, airports, oil tanks, salt works and irrigation return pumping stations 500. A location profile has been created, representing the average distance to a series of points from anywhere within a map area (Northwood Technologies Inc 2001) (Fig. 5b). The algorithm generates a grid where, at each cell, a value is calculated that represents the weighted average distance to all point locations surrounding that cell, according to the relative importance weight of each point lying within a defined search radius. In the present study, a search radius of 2,000 m has been applied as it approximately corresponds to a 5-year travel time distance, taking an average groundwater velocity of approximately 1.1 m/day (Wyssling 1979), and is supposed to be the maximum radius of influence for all the above-mentioned activities.

A monotonically decreasing sigmoidal fuzzy membership function was applied in order to transform the calculated distances to a continuous set of values ranging from 0 to 255. The control points were 0, where function membership becomes 1, and 2,000, where function membership becomes 0. Distances greater than 2,000 m from concentrated activities are considered to have the same function membership value of 0, since points at those distances are not expected to be vulnerable to groundwater pollution due to these activities.

Factor 7: proximity to major rivers

Each river is a potential final receiver of treated or even untreated wastewater; hence, aquifers close to river beds, and especially those that are hydraulically connected to them, are expected to receive part of the pollutants of wastewaters. In the present study, distances to major rivers were calculated and transformed to a 0–255 scale, using a monotonically decreasing sigmoidal fuzzy membership function. Different control points were used for the three main rivers of the study area (Nestos, Evros and Ardas), which are evidently hydraulically connected to the underlying aquifers (Vergis 2000; Papadopoulos and Romaidis 2002), and for those rivers of less importance where there was no evidence of hydraulic connection to the adjacent aquifers. In that way, the control points for the first river category were 0, where function membership becomes 1, and 1,000 m, where function membership becomes 0. Distances greater than 1,000 m from river beds are considered to have the same function membership value of 0. In the same way, control points for the second river category were 0, where function membership becomes 1, and 500 m, where function membership becomes 0 (Fig. 6a).

Factor 8: proximity to residential areas

While analyzing the non-concentrated land use factor, a land use category has been the urban one. Besides the presence of an urban center, groundwater vulnerability to pollution is also influenced by the number of inhabitants as well as by the distance to any potential aquifer. These are two parameters that were not incorporated in the land use factor. A zone of influence around each city, town and human settlement has been created, with the radius proportional to their inhabitants, according to the 2001 census data provided by the National Statistical Service of Greece (Fig. 7a). Each zone of influence has been assigned the value of the town population; thus, urban areas with a higher population are considered to have influence in greater distances and to a higher extent.

A monotonically increasing sigmoidal fuzzy membership function was used to convert data to a 0–255 scale, i.e., the vulnerability of groundwater to pollution increases proportionally to the population. The control points were set to 56,000 (the city with the highest population in the study area), where the fuzzy membership function becomes 1, and 0, where fuzzy membership function becomes 0, i.e., groundwater vulnerability is diminished in areas with no population present.

Factor 9: areas protected by national law or international environmental treaties

The study area contains wetlands of international interest, such as the delta of the river Evros, the delta of the river Nestos and the lakes Vistonida and Ismarida. Several areas belong to the European network Natura 2000 (Dafis et al. 1997) or to National Parks (Greek Ministry of Environment, Physical Planning and Public Works 1986, 1996, Pavlikakis and Tsihrintzis, 2005) and should be protected according to the Greek law, EU conservation policies or international treaties, such as the Ramsar Convention of 1971 (Fig. 7b). Most industrial and agricultural activities are prohibited in these areas; thus, the presence of such protected regions can be considered as a protective factor to groundwater pollution. In this case, two distinct categories were assigned: the first category includes all areas that belong to National Parks, Natura 2000 sites, National Forests and other protected regions, and received a value of 0 (least vulnerability to pollution), whereas all other areas received a value of 255 for this particular factor.

Factor 10: proximity to highways and railways

Highways and train railways are the main routes of transport for harmful chemicals and are potential sources of groundwater pollution, in case of an accident. Thus, a zone of influence of 500 m was created for highways and railways of the study area (Fig. 6b). A monotonically decreasing sigmoidal fuzzy membership was applied to transform distances to the 0–255 scale. The control points were set to 0 (highest vulnerability), where the membership function equals 1, and 500 (the distance of influence in case an accident occurs), where the fuzzy membership function becomes 0.

Factor group 3: assignment of aquifer vulnerability related to the presence of local geological conditions

Factor group 3 comprises two factors related to the presence of particular geological conditions that locally influence the aquifer system. These factors are the presence of geothermal fields and the presence of salt water intrusion zones, which are two common features in the study area (Fig. 8).

Factor 11: presence of geothermal fields

Several geothermal fields are present in the study area, influencing both the temperature and chemistry of groundwater (Fig. 8a). Known geothermal fields were delineated and received a value of 255, whereas a zone of influence of 500 m around each known geothermal borehole or spring has been created. A monotonically decreasing sigmoidal fuzzy membership function was applied in order to transform the distances away from geothermal boreholes or springs to a continuous set of values ranging from 0 to 255. The control points were set to 0, where function membership becomes 1 (highest vulnerability), and 500, where function membership becomes 0 and groundwater vulnerability is diminished and becomes independent of distance.

Factor 12: presence of salt water intrusion zones

In areas close to the coast and where geological conditions are favorable, salt water intrusion has been detected at distances even 10 km away from the coast. Areas of salt intrusion were delineated in the study area, according to borehole data (Petalas 1997) (Fig. 8b). However, the influence of salt intrusion is considered to diminish proportionally to the distance from the coast; thus, a monotonically decreasing sigmoidal fuzzy membership function was applied, with control points set to 0 (coastline, highest groundwater vulnerability), where the function becomes 1, and 10 km away from the coast (lowest groundwater vulnerability), where function membership becomes 0 and groundwater vulnerability is diminished and becomes independent of the distance from the coast.

Aggregation procedure and results

After standardizing all factors to a common 0–255 scale, using fuzzy membership functions, factor weights were given to all factors in each group. The weights indicate a factor's importance, relative to all other factors, and they control how factors compensate for each other. In other words, the degree to which a factor compensates for another is determined through its factor weight. In the case of determining groundwater vulnerability to pollution, factors with low groundwater vulnerability to pollution in a given location can compensate for other factors with high groundwater vulnerability in the same location.

Factor weights sum to 1 for each factor group the project has been divided into. Several techniques exist for assigning factor weights. The simplest one could be the division of 1 into the number of factors in each factor group. However, the weights produced with this procedure are not often realistic. A more efficient way of producing factor weights is the AHP (Saaty 1977; Pavlikakis and Tsihrintzis 2000; 2003), which was first introduced into the GIS by Rao et al. (1991). In the present study, AHP has been implemented applying the module WEIGHT, incorporated in the raster GIS program Idrisi Kilimanjaro (Eastman 2003). In this module, each pair of factors in a particular factor group is examined at a time, in terms of their relative importance (Table. 2, 3, 4, 5). After all possible combinations of two factors, the module calculates a set of weights that sum to 1 and a CR. This ratio indicates any inconsistencies that may have been made during the pairwise comparison process, i.e., the probability that factor weights have been assigned quite randomly (Eastman 2003). A CR greater than 0.10 indicates that factor weights should be re-evaluated (Saaty 1977).

In order to combine information from various factors in each factor group, an aggregation procedure should be applied. The most commonly used vulnerability assessment methods, like DRASTIC, apply an aggregation technique known as the weighted linear combination (Voogd 1983), where factor scores are multiplied by their factor weight and then summed to yield the vulnerability score:

$$S = \sum w_i x_i, \qquad (2)$$

where S is the vulnerability score, w_i is the weight of factor i and x_i is the score of factor i.

However, applying the same factor weights in an extended area involves the risk of underestimating local particularities, i.e., salt water intrusion may be a factor of low or no importance for most of the study area, but a crucial factor for groundwater vulnerability in the coastal zones. Honoring the local characteristics of the system, while examining data at the regional scale, is achieved by the distinction of factors into three factor groups and by applying a second set of weights in each factor group, known as the order weights. This second set of weights controls the manner in which the weighted factors are aggregated (Yager 1988; Eastman and Jiang 1996).

After factor weights are applied to the original factors, the results are ranked from low to high groundwater vulnerability to pollution for each location. The factor with the lowest vulnerability score is then given the first order weight, the factor with the next higher vulnerability score is given the second order weight and so on. This has the effect of weighting factors based on their rank from minimum (lowest vulnerability) to maximum (highest vulnerability) value for each location. The relative skew toward either minimum or maximum of the order weights controls the level of risk in the evaluation (Eastman 2003). Additionally, the degree to which the order weights are evenly distributed across all positions controls the degree to which factor weights have influence. The procedure is repeated once for each group of factors, resulting in three intermediate vulnerability maps. The final vulnerability map is produced by aggregating the intermediate results using the same procedure.

Weighting and aggregating factor group 1: The factor weights assigned in factor group 1 are shown in Table 2.

The following order weights were assigned in factor group 1:

Order weights:	0.2	0.3	0.5
Rank:	1st	2nd	3rd

The assigned order weights show a moderate level of risk. Skew toward the factor with the higher vulnerability score shows a strict decision. The intermediate intrinsic aquifer vulnerability map is presented in Fig. 10a.

Weighting and aggregating factor group 2: The factor weights assigned in factor group 2 are shown in Table 3.

The following order weights were assigned in factor group 2:

Order weights:	0.1	0.1	0.1	0.1	0.15	0.2	0.25
Rank:	1st	2nd	3rd	4th	5th	6th	7th

The assigned order weights show a moderate level of risk and a strict decision (the three factors with the highest score share 50% of the weight, while all the rest are equally weighted). Figure 10b presents the groundwater vulnerability to pollution based on factor group 2.

Weighting and aggregating factor group 3: The following factor weights were assigned in factor group 3:

Presence of geothermal fields: 0.5; presence of salt water intrusion zones: 0.5 (factors are equally weighted). The following order weights were assigned in factor group 3:

Order weights:	0.4	0.6
Rank:	1st	2nd

Table 2 Pairwise comparison matrix for factor group 1

	Aquifer type	Hydraulic conductivity	Depth to water	Calculated factor weights
Aquifer type	1	5	3	0.6370
Hydraulic conductivity	1/5	1	1/3	0.1047
Depth to water	1/3	3	1	0.2583

9 relative to the column variable, the row variable is extremely more important, *7* relative to the column variable, the row variable is very strongly more important, *5* relative to the column variable, the row variable is strongly more important, *3* relative to the column variable, the row variable is moderately more important, *1* relative to the column variable, the row variable is equally important, *1/3* relative to the column variable, the row variable is moderately less important, *1/5* relative to the column variable, the row variable is strongly less important, *1/7* relative to the column variable, the row variable is very strongly less important, *1/9* relative to the column variable, the row variable is extremely less important, *consistency ratio* 0.03 (<0.1 acceptable)

The assigned order weights show a moderate level of risk. Skew toward the factor with the higher vulnerability score shows a strict decision. Figure 10c shows the groundwater vulnerability based on factor group 3.

Weighting and aggregating intermediate results: Intermediate results were aggregated in order to produce the final groundwater vulnerability map. Two aggregation procedures were performed that resulted in two groundwater vulnerability to pollution maps for the study area. The intermediate vulnerability maps, which resulted from the three previously examined groups, were used as factors in these final aggregation processes. Groundwater vulnerability results were grouped in five distinct classes, as shown in Table 6 (columns 3 and 4) and Figs. 9 and 10d.

A first aggregation procedure, without fitting the calculated values to observed ones, was attempted using equal weights for factor groups 1 and 2, and skewing the order weights toward the factor group that shows the greatest vulnerability score. In that way, the factor weights and order weights used in this first aggregation are shown in Table 4.

The following order weights were assigned:

Order weights:	0.2	0.3	0.5
Rank:	1st	2nd	3rd

The produced vulnerability map is presented in Fig. 10d and in percentages in column 3 of Table 6.

In the second aggregation, an attempt was made to calibrate the aggregation procedure by comparing it with measured groundwater nitrate concentration data from 141 boreholes in the northeast part of the study area, which consists of alluvial aquifers (Papadopoulos and Romaidis 2002). Rather than examining the accurate estimations of nitrate concentrations, the

Table 3 Pairwise comparison matrix for factor group 2

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Calculated weights
Factor 1	1	3	5	3	5	3	7	0.3606
Factor 2	1/3	1	3	1	3	1	5	0.1541
Factor 3	1/5	1/3	1	1/3	1/3	1/3	3	0.0546
Factor 4	1/3	1	3	1	5	1	5	0.1739
Factor 5	1/5	1/3	3	1/5	1	1/3	3	0.0728
Factor 6	1/3	1	3	1	3	1	5	0.1541
Factor 7	1/7	1/5	1/3	1/5	1/3	1/5	1	0.0299

Factor 1 surface runoff accumulation, *factor 2* non-concentrated land uses, *factor 3* areas protected by national law or international environmental treaties, *factor 4* proximity to concentrated land uses, *factor 5* proximity to residential areas, *factor 6* proximity to major rivers, *factor 7* proximity to highways and railways, *consistency ratio* 0.05 (acceptable)

comparison focused on the likelihood of a location being classified as contaminated (Dixon 2005). The categories were chosen to indicate a low anthropogenic effect (<0.5 mg/l), moderate effect (0.5–3 mg/l), moderately high effect (3–10 mg/l), high effect (10–50 mg/l) and very high anthropogenic effect (>50 mg/l) (Fig. 9). Results show a best fit when factor group 1, i.e., factors related to the hydraulic parameters of the internal aquifer system, takes most of the weight. The factor weights assigned in the final aggregation are shown in Table 5.

The following order weights were assigned:

Order weights:	0.1	0.4	0.5
Rank:	1st	2nd	3rd

The assigned order weights show a low level of risk. Aggregation is clearly skewed toward the factor with the highest vulnerability score.

A coincidence report was generated between well contamination data and the composite groundwater vulnerability map, created after integrating GIS, fuzzy logic and multicriteria evaluation methods (Fig. 9). In this report it is demonstrated that 82 wells, from the 141 tested wells, were categorized in the correct groundwater vulnerability class (those located on the diagonal of Table 7); four wells were categorized in one vulnerability class higher than the observed class (those located below the diagonal of Table 7); 41 wells were categorized in one vulnerability class lower than the observed (those located above the diagonal of Table 7); 11 wells were classified in two vulnerability classes lower and three wells were categorized in three classes lower.

Discussion

In the present study a methodology for assessing groundwater vulnerability to pollution at the regional scale has been developed, which takes into account parameters related to intrinsic aquifer properties, the external stresses and local geological conditions.

A critical issue is the standardization of factors and, specifically, the selection of function control points (inflection points) of the fuzzy membership function, which is based on an understanding of the criterion. As far as distances are concerned, inflection points are located at zero distance, up to the distance where the effect of activity under consideration on groundwater is diminished. In the case of factors of broad value range, such as runoff accumulation, a quantiles classification scheme was applied, placing an equal number of pixels into each class and control points were located at the end of the first class and the starting point of the last class (approximately upper and lower 5% of the study area).

Factor weights were assigned to the 12 factors involved in the calculation process. It is clear that the assignment of factor weights is based on previous knowledge of the aquifer's characteristics and the particularities of the study area, as well as on the experience of the scientists involved in the weight assignment process. It was attempted to develop a weight assigning process, which would be as objective as possible, by

Table 4 Pairwise comparison matrix for the final aggregation procedure

	Factor group 1	Factor group 2	Factor group 3	Calculated factor weights
Factor group 1	1	1	3	0.4286
Factor group 2	1	1	3	0.4286
Factor group 3	1/3	1/3	1	0.1429

Consistency ratio = 0.00 (best)

Table 5 Pairwise comparison matrix for the final aggregation procedure after calibration with measured data

	Factor group 1	Factor group 2	Factor group 3	Calculated factor weights
Factor group 1	1	5	7	0.7306
Factor group 2	1/5	1	3	0.1884
Factor group 3	1/7	1/3	1	0.0810

Consistency ratio = 0.06 (<0.1 acceptable)

Table 6 Distinct groundwater vulnerability categories in the study area

Groundwater vulnerability index	Vulnerability class	Percentage of the study area falling in the groundwater vulnerability class	
		Before calibration with measured data	After calibration with measured data
0–50	Low	22	11
50–100	Moderate	28	35
100–150	Moderately high	34	31
150–200	High	15	21
200–255	Very high	1	2

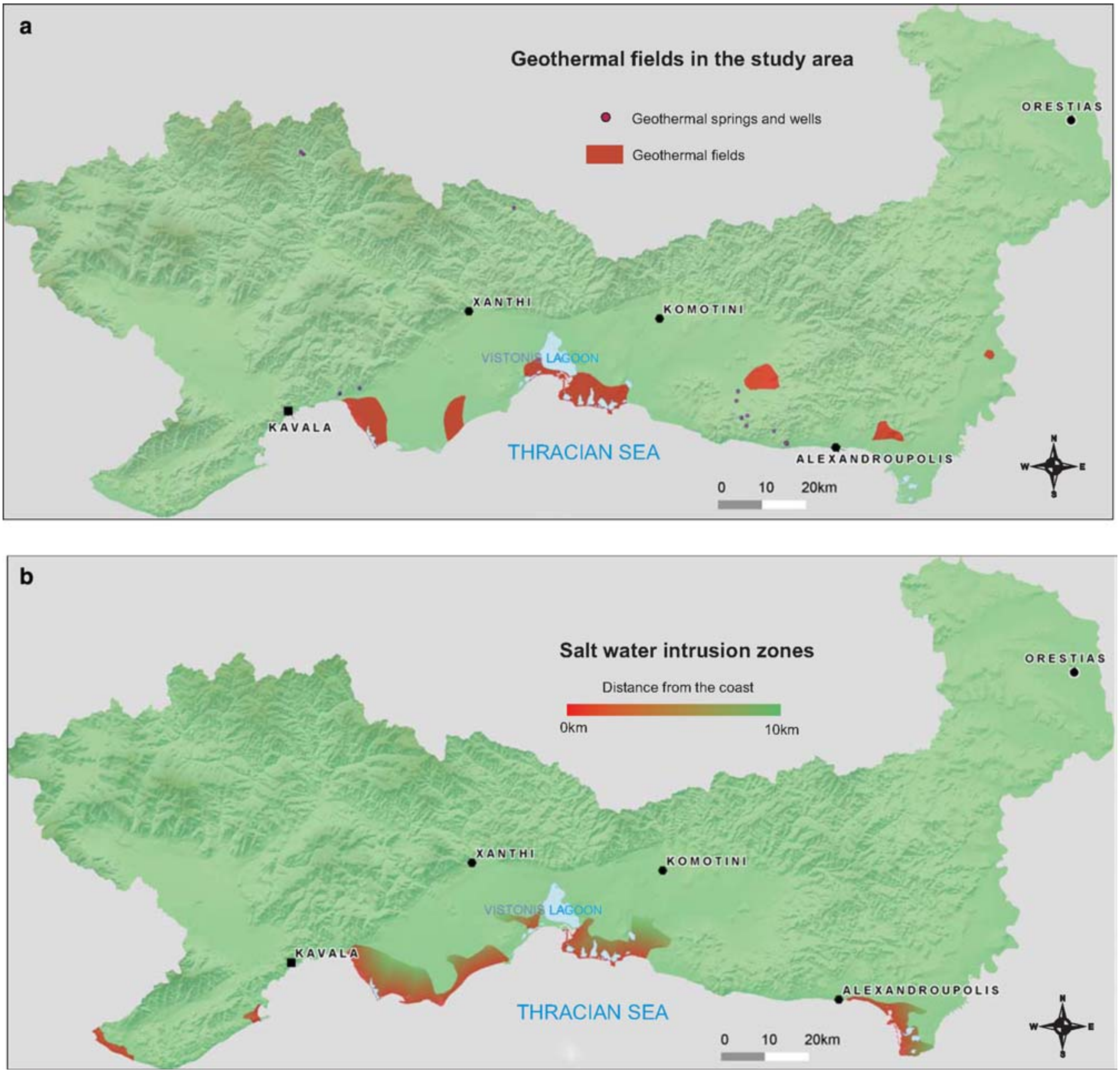


Fig. 8 Factors of local geological conditions: (**a**) presence of a geothermal field and (**b**) presence of a saltwater intrusion zone

Table 7 Coincidence of wells with five contamination levels and vulnerability classes as estimated by the presented methodology

Model	Concentration of nitrate in groundwater (mg/l)				
	Low (< 0.5)	Moderate (0.5–3)	Moderately high (3–10)	High (10–50)	Very high (> 50)
Low	13	6	4	3	
Moderate	3	11	10	2	
Moderately high		1	20	23	5
High				36	2
Very high					2

applying techniques like the AHP and the order weighted averaging. A best fit to the measured nitrate concentration data in a sub-region of the study area is achieved only when factors related to intrinsic aquifer characteristics were assigned most of the weight. This is due to the fact that, in the tested area, agricultural land uses prevail, polluting the associated aquifers with related pollutants. The main factor that differentiates contamination throughout this region is hydraulic conductivity, which is particularly low in the eastern part of this region, thus leading to lower nitrate concentrations in groundwater.

Another interesting aspect of the study is the fact that areas considered to be the most vulnerable ones, especially karst aquifers in the western part of the study area,

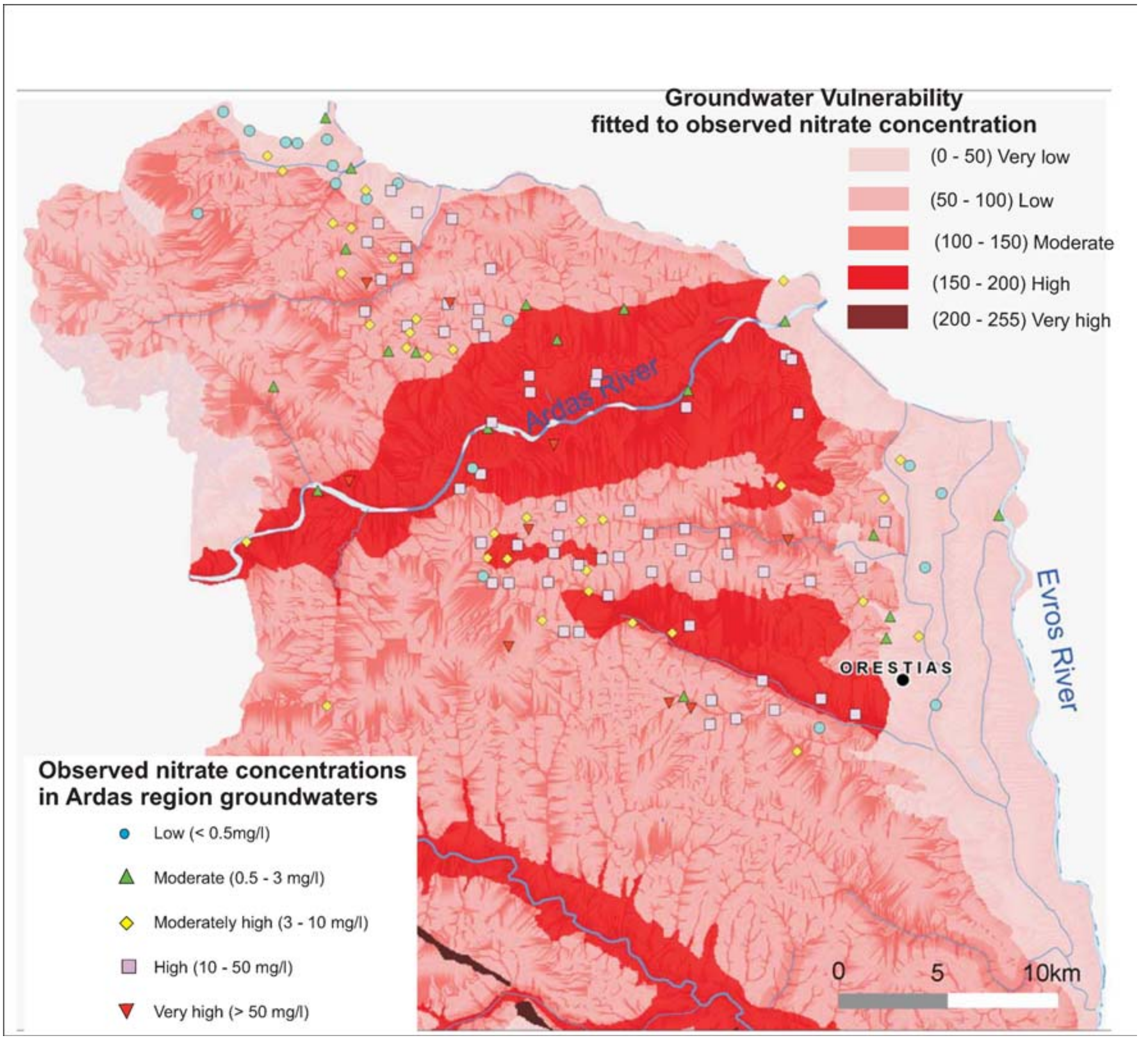


Fig. 9 Composite groundwater vulnerability map fitted to observed nitrate concentrations in groundwater

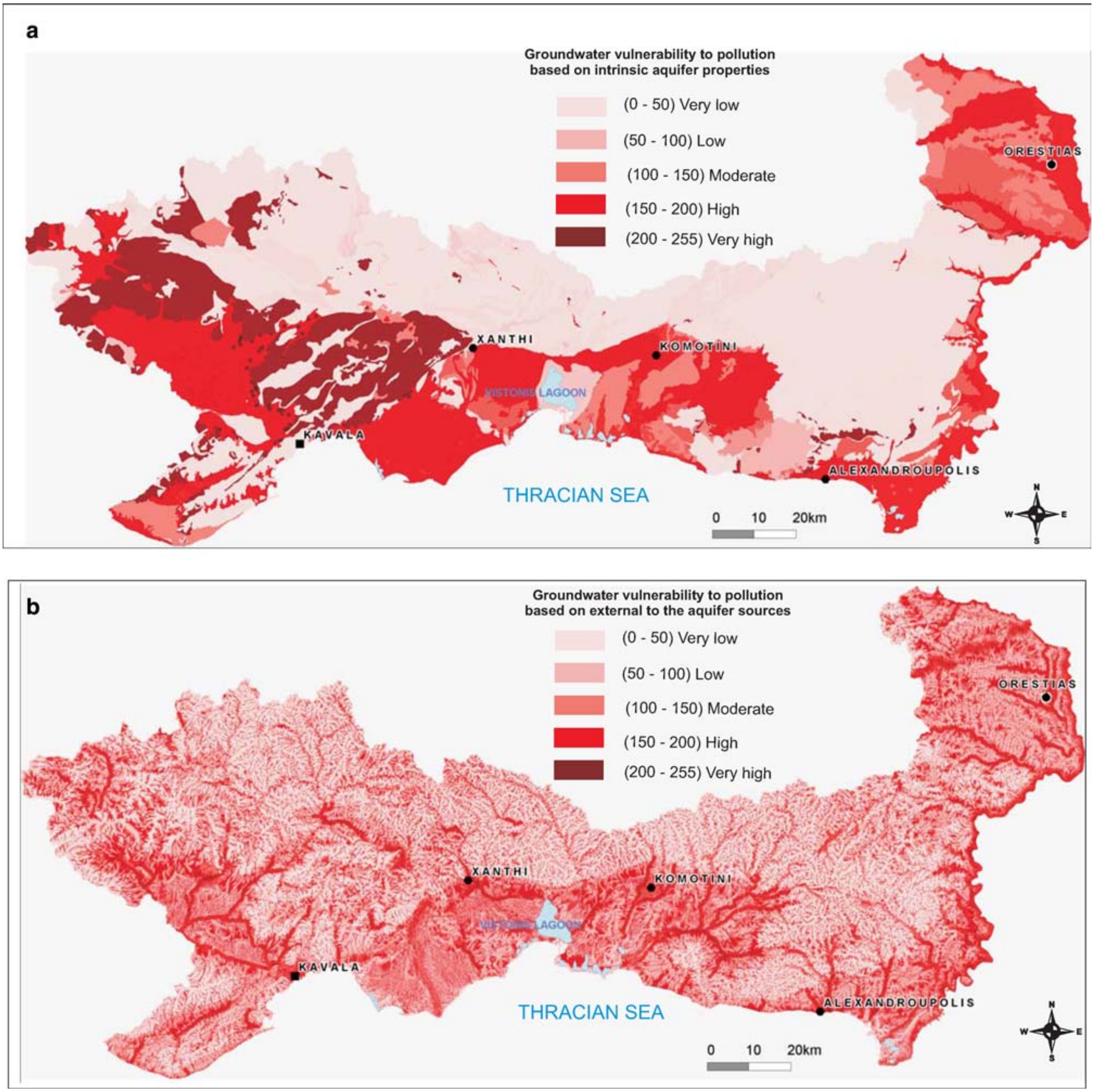


Fig. 10 Intermediate and composite groundwater vulnerability maps: (**a**) produced analyzing factor group 1; (**b**) produced analyzing factor group 2; (**c**) produced analyzing factor group 3 and (**d**) composite groundwater vulnerability map produced aggregating the three intermediate vulnerability maps

do not demonstrate contamination of their groundwater. Having in mind that groundwater vulnerability to pollution is a relative, non-measurable property (Gogu and Dassargues 2000) and that it only shows the likelihood or risk for contaminants to reach the groundwater system after introduction at some location above the uppermost aquifer (National Research Council 1993; Bekesi and McConchie 2002), one should be careful when trying a comparison between the observed and the estimated contamination of groundwater, especially in areas with contradictory properties. In addition, trying to calibrate parameters in the calculation process, such as factor weights, might lead to serious misinterpretations, especially in areas with high estimated groundwater vulnerability, where little or no contamination has been detected.

The presented work, in both aggregations used, categorizes almost 60% of the study area to moderate and

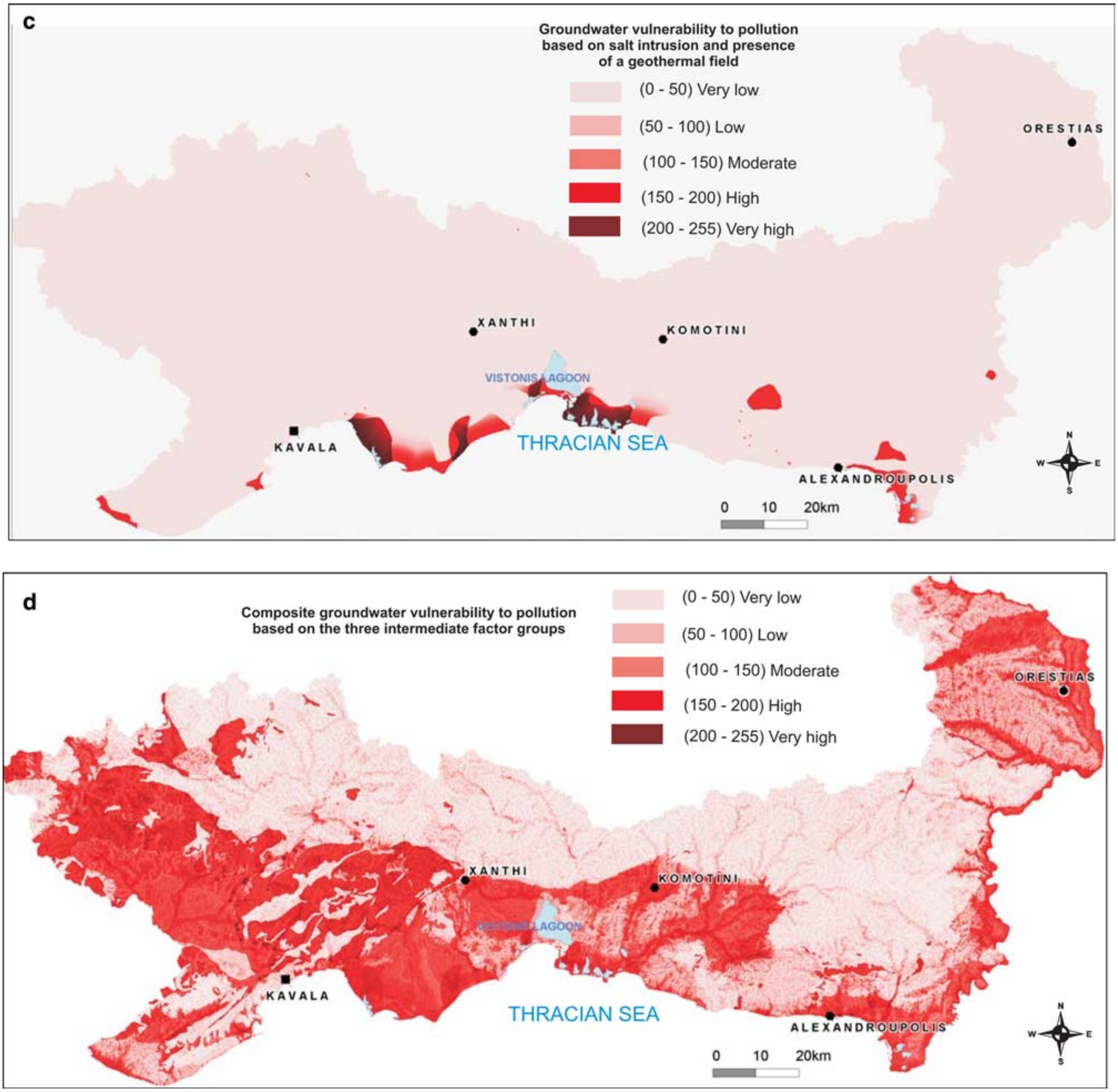


Fig. 10 (Contd.)

moderately high vulnerability classes. From this point of view the presented methodology is closer to the DRASTIC method (Aller et al. 1987) based on the comparison presented by Gogu et al. (2003). Nevertheless, DRASTIC and EPIK methods classify limestone aquifers to moderate vulnerability (Gogu et al. 2003), whereas the presented methodology assess them to high vulnerability like the German method (Von Hoyer and Sofner 1998).

Besides the differences that all the above-mentioned methods present, it is true that the choice of the vulnerability method is still a subjective decision that is restricted by the available information concerning aquifer systems. Many problems and inefficiencies are expected to be overcome when the groundwater vulnerability assignment process is coupled with groundwater flow and transport modeling, and the results are subject to correlation with observed contamination data. It is true, though, that coupling with groundwater modeling techniques is almost impossible at the regional scale, especially when karst aquifers are involved. However, results provided by groundwater vulnerability to pollution estimation at the regional scale, with the methodology outlined in the present study, are very useful for the future citing of human activities, urban development and water resources management, as well as for highlighting areas of particular interest, where coupling with groundwater modeling, at a finer scale, could offer a better understanding of the aquifer system.

Conclusions

In the present study, GIS was coupled with fuzzy logic and multicriteria evaluation techniques in order to assess groundwater vulnerability to pollution. Twelve factors were analyzed in the computation process, categorized into three main groups. Three intermediate groundwater vulnerability maps to pollution were produced that way and were combined in two ways, in order to produce the composite groundwater vulnerability map. In the first attempt, the resulted map was not fitted to observed groundwater contamination data. A second aggregation procedure, by fitting the calculated results to measured groundwater contamination data, did not produce importantly different results, indicating that the methodology is moderately sensitive to the assignment of factor weights and the aggregation procedure used. It is concluded, thus, that the applied process produces fairly objective results, a fact merely attributed to three main advantages of the presented methodology: the distinction of factors into three groups, the standardization of factors to a common scale and the application of the AHP while assigning factor weights. The application of order weights serves to highlight local particularities, making the method particularly efficient while analyzing data at the regional scale, where many aquifer types are present.

Acknowledgements The first author gratefully acknowledges the Regional Authority of Eastern Macedonia and Thrace for its support during the time needed for the completion of this study.

References

Aller L, Bennet T, Lehr HJ, Petty JR, Hackett G (1987) DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings. In: Ada OK, Robert S (eds) Kerr Environmental Research Laboratory, US Environmental Protection Agency Report EPA-600/2-87-035, pp 622

Bekesi G, McConchie J (2002) The use of aquifer-media characteristics to model vulnerability to contamination, Manawatu region, New Zealand. Hydrogeol J 10:322–331

Civita M (1994) Le carte della vulnerabilità degli acquiferiall' inquinamento. Teoria and practica (Aquifer vulnerability maps to pollution). Pitagora, Bologna

Civita M, De Regibus C (1995) Sperimentazione di alcune metodologie per la valutazione della vulnerabilità degli aquiferi. Q Geol Appl Pitagora Bologna 3:63–71

Dafis S, Papastergiadou E, Georgiou K, Babaloas D, Georgiadis T, Papageorgiou M, Lazaridou T, Tsiaousi V (1997) Directive 92/43/EEC. The Habitats project in Greece: Natura 2000 network. Contract B4-3200/84/756. DG Xi. Commission of the European Communities, Goulandris Museum of Natural History—Greek Biotope Wetland Center, p 932

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, Popescu IC, Zwahlen F (2002) Main concepts of the 'European approach' to karst-groundwater-vulnerability assessment and mapping. Hydrogeol J 10:340–345

Diamantis I (1993) Investigation of water supply possibilities of coastal settlements of Thrace from coastal aquifers. Democritus University of Thrace, Division of geotechnical engineering, Laboratory of Engineering Geology, Research project 1989–1993

Dimadis E, Gemitzi A, Karmis P (2001) Hydrogeological study of Rodopi's district mountainous area, Greece. Institute of Geological and Mining Exploration, Greece

Dixon B (2005) Applicability of neuro-fuzzy techniques in predicting ground-water vulnerability: a GIS-based sensitivity analysis J Hydrol 309:17–38

Dixon B, Scott HD, Dixon JC, Steele KF (2002) Prediction of aquifer vulnerability to pesticides using fuzzy rule-based models at the regional scale. Phys Geogr 23:130–153

Doerflinger N, Zwahlen F (1998) Praxishilfe: Kartierungder Vulnerabilität in Karstgebieten (Methode EPIK) BUWAL, Bern, pp 56

Doerfliger N, Jeannin PY, Zwahlen F (1999) Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). Environ Geol 39:165–176

Eastman JR (2003) IDRISI Kilimanjaro: Guide to GIS and Image Processing. Clark Labs, Clark University, Worcester, USA, pp 328

Eastman JR, Jiang H (1996) Fuzzy measures in multi-criteria evaluation, Proceedings, Second International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Studies, May 21–23, Fort Collins, Colorado, pp 527–534

Fetter CV (1994) Applied hydrogeology, 3rd edn. Macmillan College Publishing Company, New York, NY, pp 91

Foster SSD (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvenbooden W, van Waegeningh HG (eds) TNO Committee on Hydrological Research, The Hague. Vulnerability of soil and groundwater to pollutants, Proc Inf 38:69–86

Gogu RC, Dassargues A (2000) Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environ Geol 39:549–559

Gogu RC, Hallet V, Dassargues A (2003) Comparison of aquifer vulnerability assessment techniques. Application to the Néblon river basin (Belgium). Environ Geol 44:881–892

Greek Ministry of Environment, Physical Planning and Public Works (1986) Law 1650 for the Protection of the Environment. Official Gazette 160/A/1986

Greek Ministry of Environment, Physical Planning and Public Works (1996) Joint ministerial Decision 5796/23-3-96, Official Gazette 854/B/16-9-1996

Jenson SK, Domingue JO (1998) Extracting topographic structure from digital elevation data for geographic information systems analysis. Photogramm Eng Remote Sens 54:1593–1600

National Research Council (1993) Ground water vulnerability assessment: predicting relative contamination potential under conditions of uncertainty. Common Techniques for Assessing Ground Water Vulnerability, Water Science Technology Board, Committee for Geosciences and Environmental Resources, National Academy of Sciences, pp 204

Northwood Technologies Inc (2001) Vertical Mapper: Tutorial. Northwood Technologies Inc. and Marconi Mobile Limited, Canada, pp 133

Panilas CS (1998) Hydrogeological problems from the exploitation of black coal deposits with the method of open pit: the case of the black coal mineral deposit of Drama. Doctoral Dissertation, University of Patras, Department of Geology, Patra, Greece

Papadopoulos K, Romaidis I (2002) Hydrogeological Research of Arda's Watershed. Institute of Geological and Mining Exploration, Greece

Papadopoulos K, Favas N, Anastasiadis I, Papadopoulos P, Gemitzi A (2001) Hydrological research of Makri-Maronia area, Greece. Institute of Geological and Mining Exploration, Greece

Pavlikakis GE, Tsihrintzis VA (2000) Ecosystem management: a review of a new concept and methodology. Water Resour Manage 14:257–283

Pavlikakis GE, Tsihrintzis VA (2003) A quantitative method for accounting human opinion, preferences and perceptions in ecosystem management. J Environ Manage 68:193–205

Pavlikakis GE, Tsihrintzis VA (2005) Perceptions and preferences of the local population in Eastern Macedonia and Thrace National Park in Greece. Landsc Urban Planning, (in press)

Petalas C (1997) Analysis of aquifer systems in the heterogeneous coastal plain of Rhodope region. Doctoral Dissertation, University of Thrace, Department of Civil Engineering, Xanthi, Greece

Petalas C, Panilas SC, Diamantis J, Pliakas F (2001) Calculation and evaluation of the hydraulic parameters of two aquifers in different sedimentary environment in mass of Rhodope. Proceedings of the Ninth International Congress of the Geological Society of Greece, Athens, pp 1913–1932

Pliakas F, Diamantis I, Petalas C (1999) Environmental effects of a proposed groundwater artificial recharge project in Orfanon region of Kavala. Proceedings of the 6th International Conference on Environmental Science and Technology. Pythagorion, Samos, pp 381–390

Rao M, Sastry SVC, Yadar PD, Kharod K, Pathan SK, Dhinwa PS, Majumdar PS, Sampat Kumar D, Patkar VN, Phatak VK (1991) A weighted index model for urban suitability assessment—a GIS approach. Bombay Metropolitan Regional Development Authority, Bombay, India

Saaty TL (1977) A scaling method for priorities in hierarchical structures. Journal of Math Psychol 15:234–281

Van Stempvoort, Ewert L, Wassenaar L (1993) Aquifer vulnerability index: GIS-compatible method for groundwater vulnerability mapping. Can Water Resour 18:25–37

Vergis E (2000) Hydrogeological study of West Thrace and East Macedonia district, Greece. Institute of Geological and Mining Exploration, Greece

Von Hoyer M, Sofner B (1998) Groundwater vulnerability mapping in carbonate (karst) areas of Germany, Federal institute for geosciences and natural resources, Archive no 117854, Hanover, Germany

Voogd H (1983) Multicriteria evaluation for urban and regional planning. Pion, London

Wyssling L (1979) Eine neue Formel zur Berechnung der Zustromungsdauer (Laufzeit) des Grundwassers zu einem Grundwasser-Pumpwerk. Eclogae geol Helv 72:401–406

Yager R (1988) On ordered weighted averaging aggregation operators in multicriteria decision making. IEEE Trans Syst Man Cybern 8(1):183–190