Optimization of the DRASTIC method for groundwater vulnerability assessment via the use of simple statistical methods and GIS

G. P. Panagopoulos · A. K. Antonakos · N. J. Lambrakis

Abstract The assessment of groundwater vulnerability to pollution has proved to be an effective tool for the delineation of protection zones in areas affected by groundwater contamination due to intensive fertilizer applications. By modifying and optimizing the well known and widely used DRASTIC model it was possible to predict the intrinsic vulnerability to pollution as well as the groundwater pollution risk more accurately. This method incorporated the use of simple statistical and geostatistical techniques for the revision of the factor ratings and weightings of all the DRASTIC parameters under a GIS environment. The criterion for these modifications was the correlation coefficient of each parameter with the nitrates concentration in groundwater. On the basis of their statistical significance, some parameters were subtracted from the DRASTIC equation, while land use was considered as an additional DRASTIC parameter. Following the above-mentioned modifications, the correlation coefficient between groundwater pollution risk and nitrates concentration was considerably improved and rose to 33% higher than the original method. The model was applied to a part of Trifilia province, Greece, which is considered to be a typical Mediterranean region with readily available hydrogeological and hydrochemical data.

Résumé L'évaluation de la vulnérabilité des eaux souterraines à la pollution a montré qu'elle est un outil efficace pour délimiter les zones de protection dans les zones affectées par la contamination des eaux souterraines due à l'utilisation intensive de fertilisants. En modifiant et optimisant le modèle DRASTIC, bien connu et souvent utilisé, il a été possible de prédire la vulnérabilité intrinsèque à la pollution, et de définir plus précisément le risque de pollution. Cette méthode incorpore l'utilisation de simples techniques statistiques et géostatistiques, pour la révision des facteurs d'estimation et de pondération de tous les paramètres de DRASTIC sous S.I.G. Le critère de ces modifications était le coefficient de corrélation de chaque paramètre avec la concentration en nitrates dans les eaux souterraines. Sur la base de leur signification statistique, certains paramètres ont été soustraits de l'équation DRASTIC. Suivant les modifications mentionnées ci-dessus, le coefficient de corrélation entre les concentrations en nitrate et le risque de pollution des eaux souterraines a été considérablement amélioré de 33% par rapport à la méthode originale. Le modèle a été appliqué sur une partie de la province de Trifilia en Grèce, qui est considérée comme une région typiquement méditerranéenne avec des données hydrogéologiques et hydrochimiques aisément accessibles.

Resumen La evaluación de vulnerabilidad del agua subterránea a la contaminación ha demostrado ser una herramienta efectiva para la delimitación de zonas de protección en áreas afectadas por contaminación de aguas subterráneas debido a aplicaciones intensivas de fertilizantes. Mediante la modificación y optimización del bien conocido y ampliamente utilizado modelo DRASTIC fue posible predecir la vulnerabilidad intrínseca a la contaminación así como el riesgo a la contaminación del agua subterránea con mayor precisión. Este método incorporó el uso de técnicas estadísticas y geoestadísticas simples para la revisión del pesaje y establecimiento de rangos de factores de todos los parámetros DRASTIC bajo un ambiente SIG. El criterio para estas modificaciones fue el coeficiente de correlación de cada parámetro con las concentraciones de nitraros en agua subterránea. En base al grado significativo estadístico algunos parámetros fueros sustraídos de la ecuación DRASTIC, mientras que se consideró el uso de la tierra como un parámetro adicional de DRASTIC. Siguiendo las modificaciones antes mencionadas se mejoró considerablemente el coeficiente de correlación entre el riesgo a la contaminación del agua subterránea y las concentraciones de nitratos incrementando en 33% su valor en relación al método original. El modelo se aplicó en una parte de la provincia Trifilia, Grecia, la cual se considera ser una región Mediterránea típica con datos hidroquímicos e hidrogeológicos fácilmente disponibles.

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Introduction

Intrinsic vulnerability of an aquifer can be defined as the ease with which a contaminant introduced into the ground surface can reach and diffuse in groundwater (Margat 1968; Vbra and Zaporozec 1994). It is a relative, dimensionless and non-measurable property that depends on the aquifer characteristics as well as the characteristics of the wider geological and hydrological environment (vadose zone, soil horizon, relief, recharge, etc.).

Specific vulnerability may be expressed as the likelihood that an aquifer be polluted by contaminants which are introduced into the ground surface. This is determined by the aquifer intrinsic vulnerability and the contaminant loading that is applied to the specific point of the hydrogeological basin or even in a wider region around this point. The contaminant loading is determined by the quantity, the physico-chemical properties and the way in which the various contaminants are released into the environment.

The assessment of groundwater vulnerability to pollution has been subject to intensive research during the past years and a variety of methods have been developed. The simplest to apply, and for that reason the most widely used, are the rating models. These methods classify each parameter that potentially influences the probability of pollution of the aquifer, and lead to a score which designates the vulnerability of the groundwater (LeGrand 1964; Foster 1987; US EPA 1993).

An evolutionary product of these methods is the point count system models (PCSM) or parameter weighting and rating methods, which, apart from classifying the various parameters, also introduce relative weight coefficients for each factor.

The most widespread PCSM method of evaluation of the intrinsic vulnerability is the DRASTIC method (Aller et al.1987). This method, taking into account seven parameters of the geological and hydrological environment, was developed in the USA where it has been applied several times (Durnford et al. 1990; Evans and Myers 1990; Halliday and Wolfe 1991; Rundquist et al. 1991; Fritch et al. 2000; Shukla et al. 2000), but also in many other regions of the world (Lobo-Ferreira and Oliveira 1997; Lynch et al. 1997; Melloul and Collin 1998; Johansson et al. 1999; Kim and Hamm 1999; Zabet 2002).

In this paper, an optimization procedure of the original DRASTIC method is proposed using various modifications and transformations on the basis of the statistical parameters of a pollution index distribution. The final goal is the development of an integrated method which could successfully predict the specific vulnerability or the pollution risk of an aquifer under intense environmental stress.

The pollution index that will be used in this analysis, is the nitrates concentration (expressed as mg/L NO_3^-). The selection of this index was based not only on the fact that it constitutes the main contaminant that human activities introduce into the environment of the study area, but also because it has been proposed as a representative indicator of groundwater quality degradation (US EPA 1996).

Geological and hydrogeological setting

The study region is located in the southwestern part of the Peloponnesus, Greece, in the southwest part of Trifilia province and is approximately 285 km^2 in area (Fig. 1). The geological bedrock consists of the carbonate sediments and flysch of the Tripolis zone (Fig. 2, Perrier 1980). The upper members of the carbonate series are composed of bituminous Eocene limestones, dolomites and dolomitic limestones and are uncomformably overlain by the turbiditic sequence of flysch which is distinguished in two individual units. The lower unit (Oligocene) includes the fine flysch phase, comprised mainly of alternating beds of blue siltstones, shales, sandstones and marls. The flysch conglomerates (U. Oligocene–M. Miocene) comprise the upper unit of this sequence, including very well-rounded pebbles and cobbles mainly of limestone, dolomite and, to a lesser extent, sandstone and chert. The post orogenic sediments occupy an important part of the region (Fig. 2) and are found in transgressive discontinuity with the bedrock formations. The marly limestones comprise the lower unit of these sediments (Pliocene) and consist of calcareous fragments within a marly cement. The Pleistocene sediments take up the larger part of the study area, consisting of calcareous sandstones, sands, gravels and conglomerates, while at the easternmost part of the Eocene limestones, the sequence becomes finer, dominated by sandy clay, sandy loam and clay. The palaeosols (mid to late Pleistocene) comprise purple-red siliceous soils, mainly consisting of angular, corroded grains of red chert. The alluvial deposits are modern fluvial sediments (Holocene), consisting of boulders, pebbles and cobbles mainly of sand, sandy loam and clay loam composition.

From the hydrogeological point of view, the most important aquifer is the Trifilia karst aquifer, with an average thickness of 70 m, forming in the karstified carbonate bedrock sediments. The transmissivity, hydraulic conductivity and specific yield have extremely high values, with an average of 1,511 m^2/day, 21.6 m/day and 5%, respectively (Panagopoulos 2004). The general groundwater flow is NNW–SSE and the mean hydraulic gradient rises to 0.6‰, an indication of high aquifer permeability. The Trifilia karst aquifer is directly recharged by precipitation, although a remarkable recharge component constitutes the indirect infiltration through the streambed of the drainage network of the study area (Panagopoulos 2004).

The flysch conglomerates form an important unconfined aquifer, mainly discharged by springs in their contact with the fine flysch phase and recharged directly from precipitation. The mean aquifer thickness ranges from 10 to 60 m and the mean transmissivity and hydraulic conductivity are 499.8 m^2/day and 21.4 m/day, respectively (Panagopoulos 2004).

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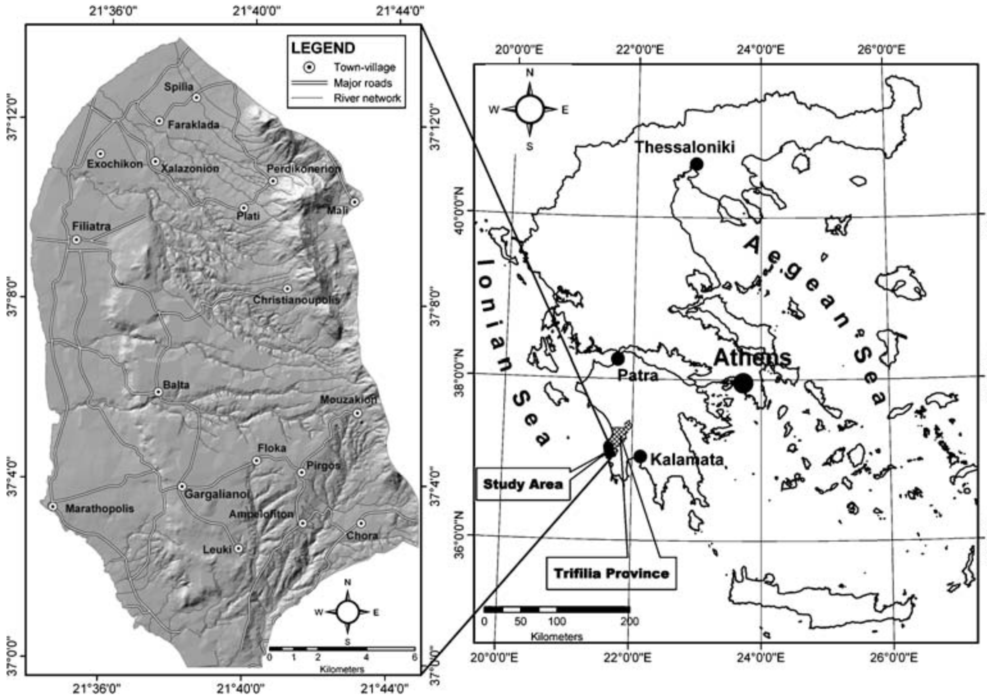

Fig. 1 Relief and geographic orientation map of the study area (SW part of Trifilia province)

The Pleistocene sediments host an extensive unconfined aquifer, with a mean thickness of 8 m, while the mean transmissivity, hydraulic conductivity and specific yield is 157.3 m^2/day, 20.7 m/day and 16.4%, respectively (Panagopoulos 2004). The groundwater flows generally from east to west towards the Ionian Sea, with a hydraulic gradient ranging from 0.9 to 5.7%, and receives the recharge directly from precipitation.

The palaeosols and alluvial deposits form two insignificant unconfined aquifers, owing to the small thickness of the vadose zone. However, they cover local irrigation demands and, for this reason, are included in the proposed model.

The annual precipitation at Trifilia region is 818 mm, which corresponds to a mean annual rainfall volume of 231.1×10^6 m^3. The water balance parameters have been computed based on the procedures described by Thornthwaite and Mather (1955). Of the annual precipitation, 54.41% (125.7×10^6 m^3) is lost via evapotranspiration, while 26.91% (62.2×10^6 m^3) infiltrates and recharges the groundwater. The remaining 18.68% (43.2×10^6 m^3) discharges to the sea as surface runoff (Panagopoulos 2004).

A widespread agricultural practice in the area is the use of inorganic fertilizers, which has a polluting effect on groundwater. According to Sampatakakis et al. (1994), the mean annual amount of fertilizers applied in Trifilia area is 1,850 kg/ha. Compositions of these fertilizers have changed during the last decades. In 1960, 70–80% of the fertilizers were ammonium sulphate $(NH_4)_2SO_4$, 10–15% were ammonium nitrate (NH_4NO_3), 10–15% were mixed nitrogen (N), phosphorous (P) and potassium (K), and the remaining 5–10% were trace elements. In 1970, these values changed to 50–60, 25-30, 20–30 and 5–10% respectively, while in 1980, the percentage contribution was 20–30, 30–40, 30–40 and 10% respectively.

Materials and methods

Sampling and analysis

Bores were flushed by turning on the bore pump and allowing it to run for approximately 30 min until groundwater was freshly drawn from the aquifer. Groundwater samples were collected in the dry period of the 2001 hydrological year at a sampling network which includes 145 sampling points, covering the whole range of the DRASTIC parameters (drastic parameters defined for these sample points show great range of values). Plastic 500-ml bottles were filled with the groundwater sample, filtered through a Millipore filter paper (0.45 μm), and stored in an insulated cooler until they were frozen later in the day. Samples were analyzed for NO_3^- by the cadmium reduction method, using a DR/4000 Hach spectrophotometer.

Soil samples were taken at 46 sites, covering the whole range of the Trifilia topsoil types. Soils were sampled using a 2.5-cm diameter tube auger and the cores were bulked and stored in large polyethylene bags. Grains larger than sand (diameter > 2 mm) were determined by sieves, while smaller grains (< 2 mm) were determined by the 'pipette method' (McKeague 1978).

Methodology of determination of aquifer specific vulnerability: the DRASTIC method

Predicting the degree of pollution of an aquifer due to the application of a contaminant such as nitrates, using data from the geological and anthropogenic environment,

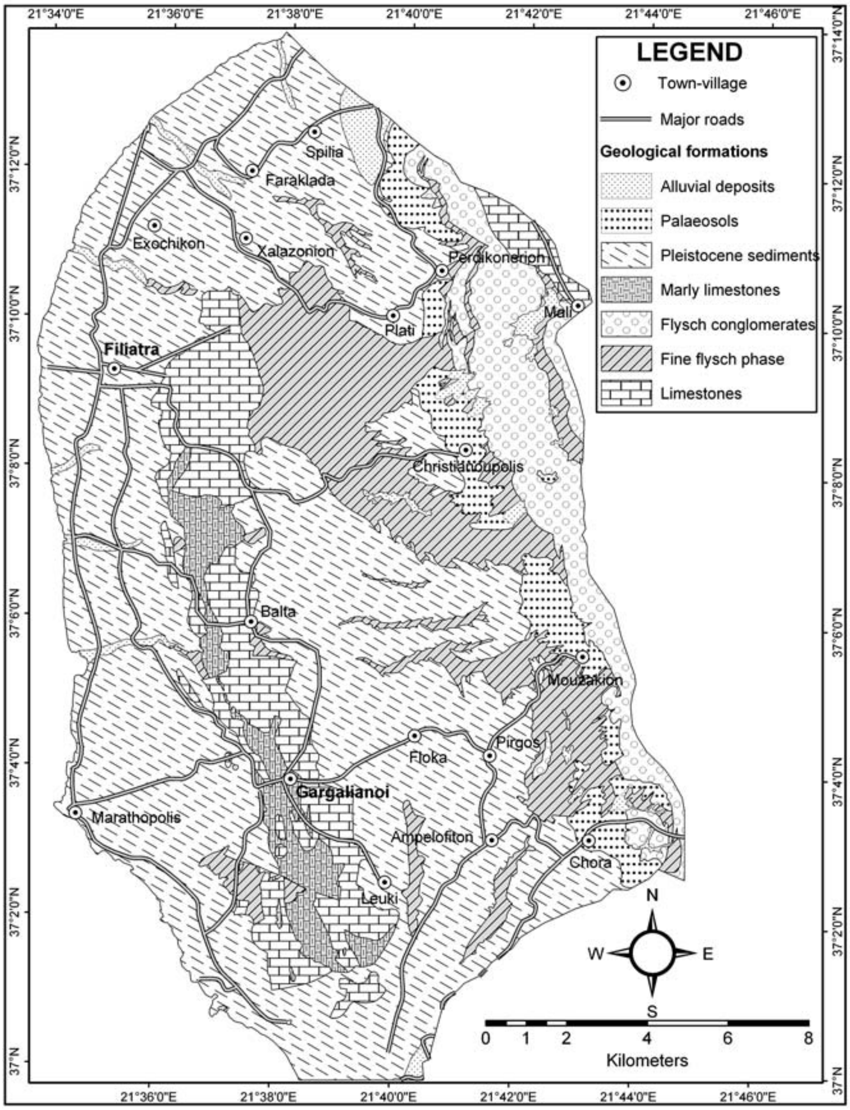

Fig. 2 Geological map of the study area

constitutes an issue of priority and major practical importance.

In this paper, intrinsic vulnerability is assessed using the DRASTIC method. This method includes a hydrochemical data set and the recording of the anthropogenic loadings into the groundwater based on the distribution of land use and the contaminant loading that each land use introduces into the natural environment.

The DRASTIC method considers seven parameters, which taken together, provide the acronym. They include: Depth to groundwater, Recharge, Aquifer type, Soil type, Topography, Impact of the vadose zone, hydraulic Conductivity.

These parameters are imported in a simple linear equation after they have been reduced from the physical range scale to a ten-grade relative scale. Each parameter is multiplied by a weighting coefficient which has been determined with qualitative, not with quantitative criteria, based on the judgment of the authors of this method. The reduction of the physical range scale to the relative ten-grade scale is conducted with the same philosophy. The linear equation of determination has the following form:

$$V_{(\text{intrinsic})} = D \cdot \lambda_D + R \cdot \lambda_R + A \cdot \lambda_A + S \cdot \lambda_S + T \cdot \lambda_T + I \cdot \lambda_I + C \cdot \lambda_C \tag{1}$$

where $V_{\text{intrinsic}}$ is the intrinsic vulnerability, D is the depth to groundwater, R is the recharge, A is the aquifer type, S is the soil type, T is the topography, I is the impact of the vadose zone, C is the hydraulic conductivity and λ is the weighting coefficient for each factor.

The major drawback of this method is the subjectivity of the determination of the rating scale and the weighting coefficients. Doubts have also been expressed for the selection of the specific parameters and the exclusion of others. In brief, the DRASTIC method has been criticized on the following points:

- So many variables are factored into the final index that critical parameters in groundwater vulnerability may be

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subdued by other parameters that have no bearing on vulnerability for a particular setting (Vbra and Zaporozec 1994; Merchant 1994).

- The selection of the parameters is based on qualitative judgment and not quantitative studies (Garrett et al. 1989).
- Many important scientifically defined factors, e.g. sorption capacity, travel time and dilution are not taken directly into account (Rosen 1994).
- The system tends to overestimate the vulnerability of porous media aquifers compared to aquifers in fractured media (Rosen 1994).
- A test of the accuracy of the model is very difficult to carry out, because it requires that a pollutant with the properties assumed by the model (introduced into the ground surface, flushed into the groundwater via precipitation and the mobility of water) be deposited all over the test area with a uniform concentration and for a considerable time period of several years to allow the hydrogeological setting to respond (Rosen 1994).

Despite these criticisms, many advantages of the DRASTIC and similar other methods have been recognized:

- The method has a low cost of application and can be applied in extensive regions, because of the relatively few, and easy to collect, data required (Aller et al. 1987).
- The selection of many parameters and their interrelationship decrease the probability of ignoring some important parameters, restrict the effect of an incidental error in the calculation of a parameter and so enhance the statistical accuracy of the model (Rosen 1994).
- This method gives relatively accurate results for extensive regions with a complex geological structure, despite the absence of measurements of specific parameters that the most specialized methods would require (Kalinski et al. 1994; McLay et al. 2001).

Improvements of the DRASTIC model have been proposed by several researchers. Most of them propose the subtraction of factors included in the model (Evans and Myers 1990; Rupert 1999) or the inclusion of additional factors like land use or irrigation type and intensity (Secunda et al. 1998; Rupert 1999; McLay et al. 2001). Finally proposals about incorporating DRASTIC with other procedures or models, like capture zone delineation or finite element flow and transport models, have been made (Foster 1987; Merchant 1994)

Fewer attempts have been made to validate and verify the model performance. In most cases, correlation of model results with actual pollution occurrence was used for that purpose. (Kalinski et al. 1994; Rupert 1999; McLay et al. 2001).

Rupert (1999) uses the same basic idea and the same simple statistical methods as the present paper to improve the groundwater vulnerability assessment, but, there are several issues concerning the overall procedure he is using:

- The initial model used for improvement is actually not DRASTIC but a modification of DRASTIC in which important factors of the model, like impact of the vadose zone and aquifer type, have been arbitrarily excluded.
- The improvements concerned only factor ratings and not factor weights which were subjectively chosen.
- Land use types were used not as a contaminant loading indicator but as the major factor affecting groundwater recharge.
- Correlation between actual pollution occurrence and the vulnerability score derived by the model was semi-quantitative since the vulnerability score was expressed in classes (low, medium, high) and not as absolute values.

The methodology developed in this paper for the evaluation of pollution risk attempts to utilize all of the aforementioned advantages, maintaining the basic structure of the DRASTIC model, while, at the same time, with various transformations and additions, aiming to improve it.

The criterion for the effectiveness of these transformations is the value of the correlation coefficient of the "aquifer vulnerability" and "nitrates concentration" parameters. Correlation of these two parameters introduces an inherent risk in the procedure used in this study because actual

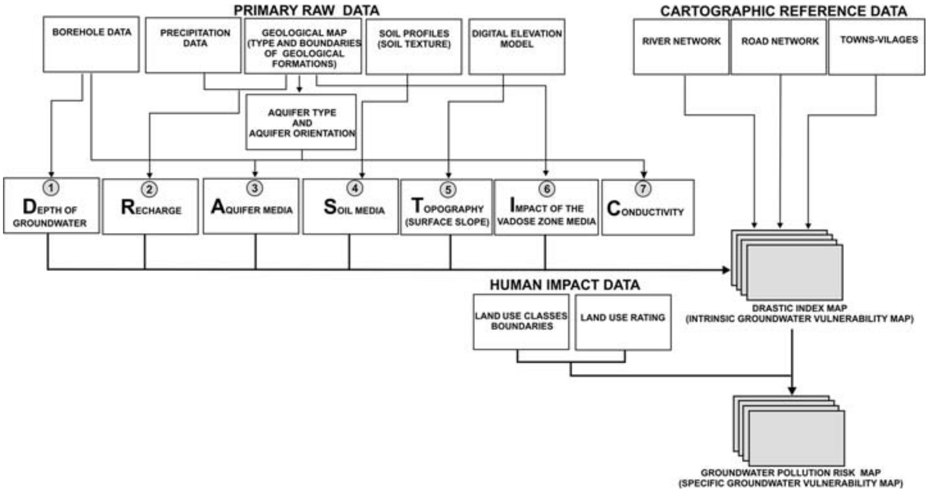


Fig. 3 Schematic representation of the processes used to determine DRASTIC intrinsic vulnerability map and groundwater pollution risk map

Fig. 4 Distribution of DRASTIC intrinsic vulnerability and nitrates concentrations for the study area

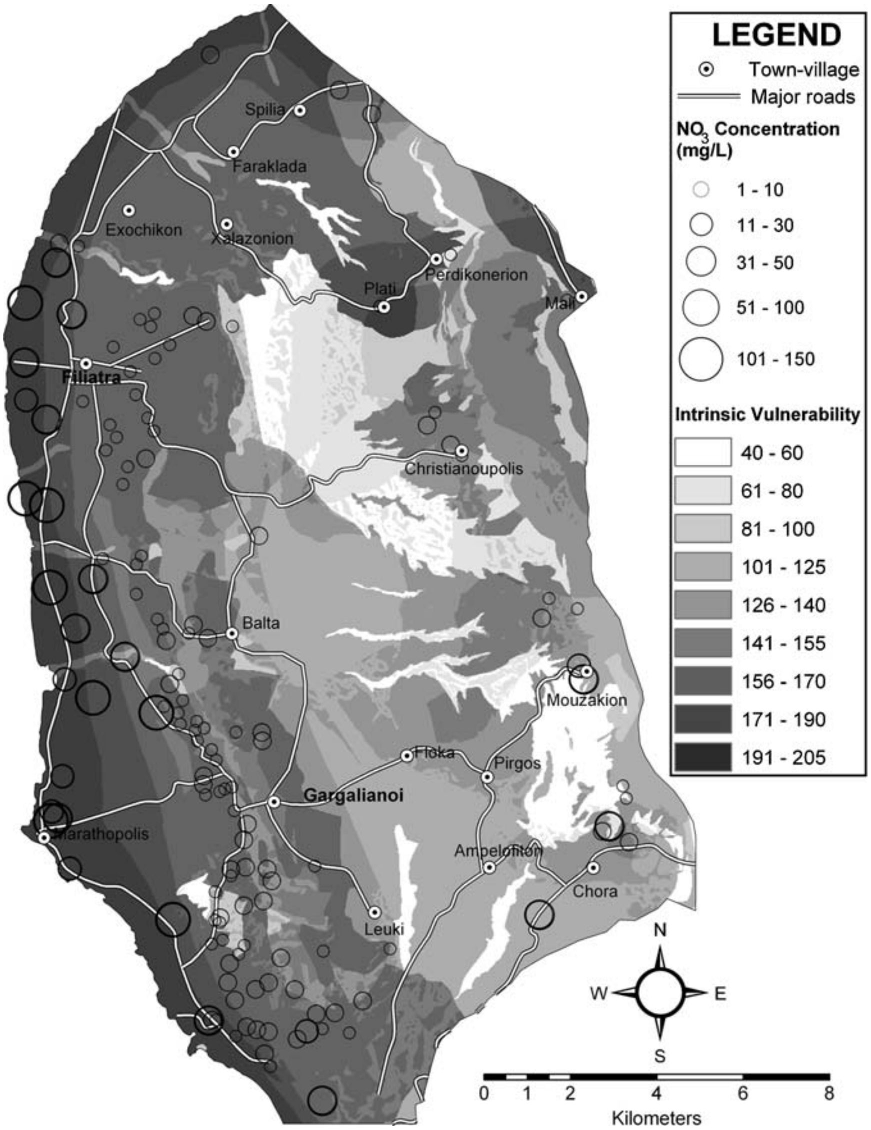
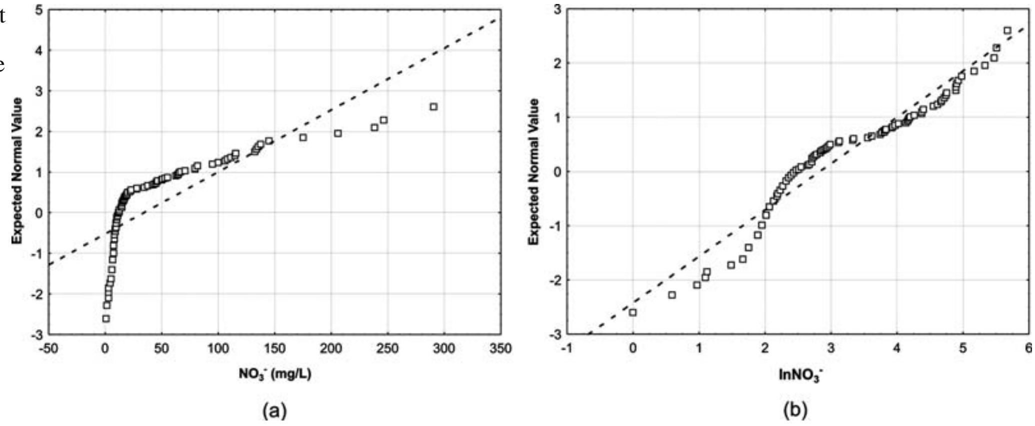


Fig. 5 Normal probability plot of nitrates concentration in groundwater samples (**a**) before and (**b**) after logarithmic transformation



pollution occurrence (nitrates concentration) at a point is defined not only by the ease with which a contaminant can reach and diffuse in groundwater (a parameter estimated by the DRASTIC model), but also by the contaminant loading that is applied to the same point. Nevertheless, one must consider that there is no measurable physical or chemical property that can be directly correlated with intrinsic vulnerability estimated by the DRASTIC model. Thus, the

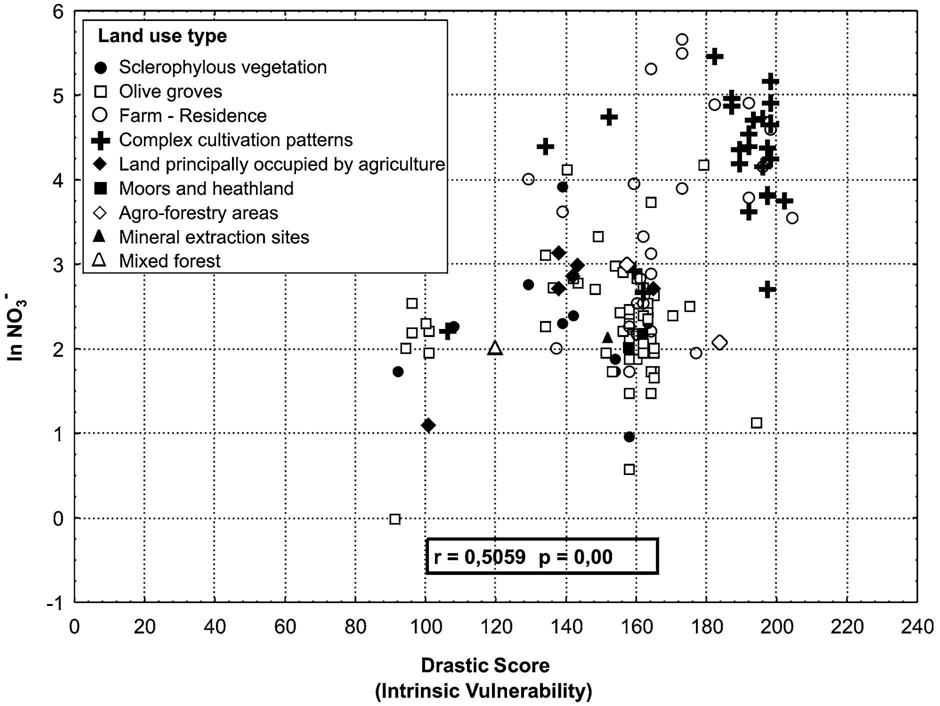


Fig. 6 Relationship of DRASTIC intrinsic vulnerability index and groundwater nitrates concentration (logarithmically transformed) for the study area

only way to check model efficiency is to assume that contaminant loading does not introduce much difference between intrinsic vulnerability and pollution risk (specific vulnerability), a property that can be directly related to actual pollution occurrence.

As it was revealed by the results of the present study, the introduction of contaminant loading in the DRASTIC equation contributes very little to the correlation of actual pollution occurrence with the score derived from the model equation. This can be attributed to the common variation of contaminant loading with some of the DRASTIC factors like depth to groundwater or surface slope. This common variation occurs because land-use types that produce large contaminant loading, like cultivations or urban areas, are located in low relief areas (coastal plains, river plains, etc.) where surface slope and groundwater depth are relatively small. So, one must regard the above mentioned assumption as quite reasonable, at least for the study area of the present paper.

Many other researchers seem to find this assumption reasonable, since they have tried to correlate intrinsic vulnerability (derived by DRASTIC or other similar models) with actual pollution occurrence expressed by nitrates concentration (Rupert 1999; McLay et al. 2001) or other contaminants, like volatile organic chemicals (Kalinski et al. 1994).

For the application of the DRASTIC method, the conditions that contaminants such as nitrates must meet are:

- Must be derived from the agricultural activities which have been carried out in the research area for more than 20 years.
- Have the mobility of the groundwater.
- Are flushed into the groundwater by precipitation.
- Are relatively uniformly distributed over most parts of the research area.

The research area also combines other features essential for guaranteeing the statistical accuracy of the method:

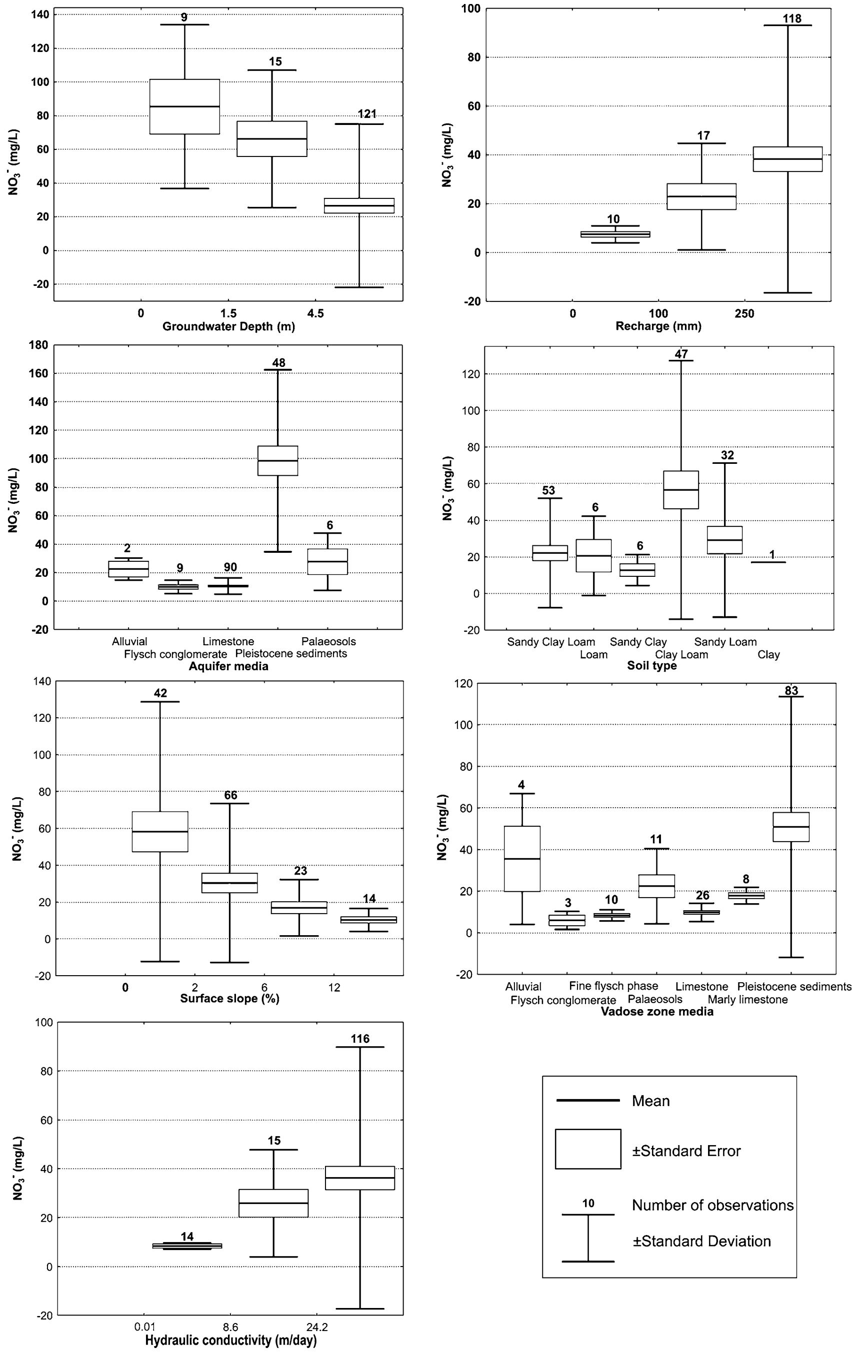
- It presents a broad range of the values for all the model parameters, since it contains largely different geological formations, aquifer types with wide ranges in the hydraulic and geometrical properties, different soil types, aquifer depth and recharge.
- The concentration of the pollution index, i.e. nitrates, exhibits a large range in values, while the sampling points are distributed in areas that almost entirely cover the range width of all the model parameters.

Figure 3 outlines the initial data that were used for the DRASTIC method application as well as the total flowchart for the intrinsic vulnerability determination under a Geographical Information System (GIS) environment.

Application of the original DRASTIC method in Trifilia

After the application of the original method, the distribution of the intrinsic vulnerability values is shown in Fig. 4. For reasons of geographical collation, the nitrates concentrations are plotted in the same figure with graduated symbols. A relative coincidence of the high nitrates and vulnerability values is observed. An over-estimate of the vulnerability values is shown in the zone between Filiatra and Gargalianoi, namely in the karst aquifer of the research area with relatively high hydraulic parameter values

Fig. 7 Box plots showing the distribution of groundwater nitrates concentration for the statistically different classes of all the DRASTIC parameters



and where the groundwater is found at a relatively great depth. These observations lead to the conclusion that the DRASTIC method over-estimates the vulnerability values in the karst aquifer of the study area, which is in contrast to findings in other regions (Rosen 1994).

The improvement of the initial application of the DRASTIC method depends on the correlation between the vulnerability and nitrates concentration values for the 145 sampling points. This correlation is expressed by the Pearson's (r) correlation factor (Pearson 1896) and the shape of the respective distribution diagram. The application of Pearson's (r) correlation factor presupposes a normal distribution of the nitrates concentration values, a condition which is not satisfied for the data of the research area, as is shown by the statistical significance of the Shapiro–Wilk's test ($p = 0$)(Shapiro et al. 1968) and in the left side normal probability plots of Fig. 5a.

Following a logarithmic transformation of the nitrates concentrations (Fig. 5b), the correlation between vulnerability and nitrates concentration has been recalculated. As is illustrated in Fig. 6, the relationship between the two parameters, however statistically significant ($p = 0.00$), is not explicit enough and the Pearson's (r) correlation coefficient is low, in the order of 0.5.

Table 1 Original and modified ratings of the seven DRASTIC factors

Depth to groundwater				Recharge				Aquifer type				Soil type			
Range (m)	Original rating	Mean NO_3^- (mg/L)	Modified rating	Range (mm)	Original rating	Mean NO_3^- (mg/L)	Modified rating	Aquifer type	Original usual rating	Mean NO_3^- (mg/L)	Modified rating	Soil type	Original rating	Mean NO_3^- (mg/L)	Modified rating
0–1.5	10	85.4	10	0–50	1	7.5	1.8	Alluvial	5	22.5	3	Clay	1	17.0	3
1.5–4.5	9	66.2	7.7	50–100	3			Conglomerate	4	10.2	1.2	Clay loam	3	56.6	10
4.5–9	7			100–180	6	22.9	6	Limestone	8	10.6	1.4	Sandy clay loam	4	22.1	3.7
9–15	5			180–250	8			Pleistocene	7	98.6	10	Loam	5	20.6	3.5
15–23	3	26.6	3.1	250+	9	38.3	10	Palaeosols	6	24.3	3.7	Sandy clay	5	12.8	2.2
23–30.5	2											Sandy loam	6	29.1	5
30.5+	1														

Topography				Impact of the vadose zone				Hydraulic conductivity			
Range slope (%)	Original rating	Mean NO_3^- (mg/L)	Modified rating	Geological formation	Original usual rating	Mean NO_3^- (mg/L)	Modified rating	Range (m/day)	Original rating	Mean NO_3^- (mg/L)	Modified rating
0–2	10	58.2	10	Alluvial	8	35.5	9.2	0.01–1.3	1	6.9	2.2
2–6	9	30.4	5.3	Conglomerate	6	5.9	1.5	1.3–3.9	2		
6–12	5	16.9	2.9	Fine Flysch phase	3	8.3	2.1	3.9–8.6	4		
12–18	3	10.3	1.7	Palaeosols	6	22.4	6.3	8.6–13	6	25.9	7.7
18+	1			Limestone	6	9.5	2.6	13–24.2	8		
				Marly limestone	6	16.7	4.7	24.2+	10	36.2	10
				Pleistocene	6	49.5	10				

Aiming at a better prediction, an optimization of the methodology was attempted based on the:

- Revision of the rating scale of each parameter.
- Revision of the factor weights.
- Addition and subtraction of parameters, without dramatically altering their final number and ignoring the property of each parameter.

Revision of the rating scale of each parameter

A revision of the rating scales can be accomplished by using the mean of every class of each parameter defined in the initial model. Following the check that was carried out using the Wilcoxon rank-sum nonparametric statistical test (Wilcoxon 1945), it was ascertained that the mean of two neighbouring classes did not differ statistically. Classes were grouped in such cases, while for non-continuous parameters (parameters with discrete classes, e.g. aquifer type, vadose zone type and soil type), all the categories existing in the area were maintained, regardless of statistical diversity. The box plot diagrams of all the statistically divergent classes of all the DRASTIC parameters are illustrated in Fig. 7. In Table 1, the parameter classes, as well as the corresponding rating of each class, the average nitrates concentration and the respective modified rating of every class or group of classes are presented. Modified rating values were derived using the mean nitrates concentration of each class reduced to a ten-grade scale.

From Figs. 4–7 and Table 1 it is concluded that:

- In all the continuous parameters (depth to groundwater, recharge, relief, hydraulic conductivity), the means of the nitrates concentrations follow the same ascending or descending course with the respective natural range values, as well as with the relative factor rates of each class.
- The nitrates concentration values in the limestones have a low range.

Following the revision of the rating scales, the applied modified DRASTIC model increases the correlation coefficient with the nitrates concentration to the value r=0.68 (Fig. 8). Apart from the coefficient value, the improvement of the correlation is obvious from the shape of the diagram as well as from the study of the respective map (Fig. 9), where in the zone with the larger divergences (limestones formation), a clear decrease of the vulnerability values is observed, which is in agreement with the nitrates concentration values.

Revision of the weighting factors: parameter subtraction

The next step of the initial model modification is the revision of the weighting factors with which each DRASTIC parameter participates in Eq. (1). This revision is achieved by the study of the correlation of each parameter with the nitrates concentration for the 145 sampling points of the

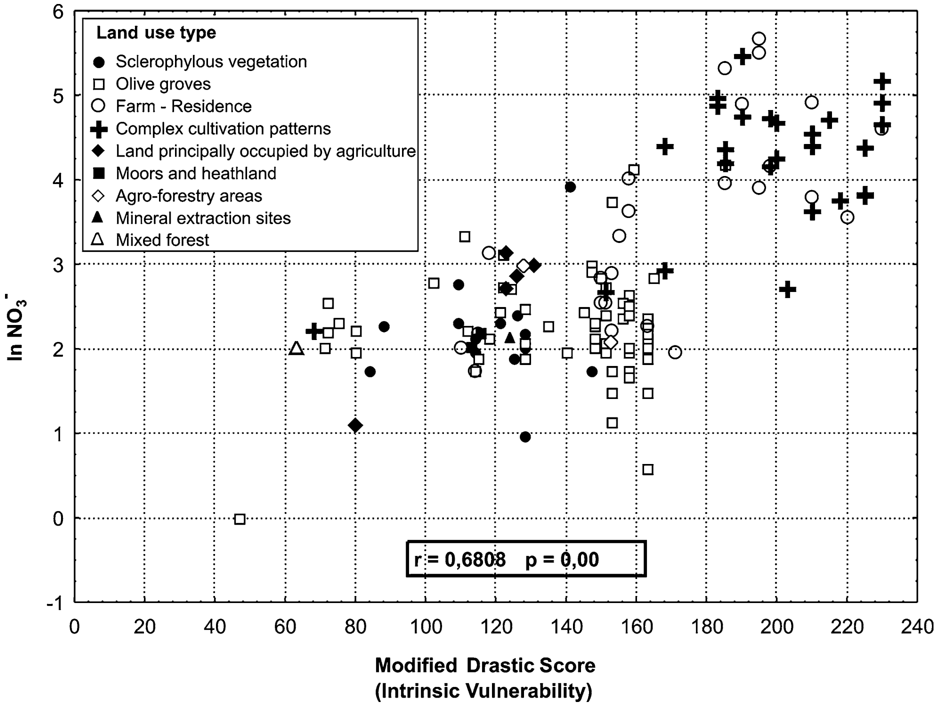


Fig. 8 Relationship of modified (modified factor ratings) DRASTIC intrinsic vulnerability index and groundwater nitrates concentration (logarithmically transformed) for the study area

research area. For the calculation of the quantitative correlation between the nominal parameters and the nitrates concentration, the factor scores, and not the natural range values, were used. Additionally, due to the fact that the factor scores vary with an interval scale, the correlation was calculated using the Spearman's rho and Kendall's tau correlation coefficients (Kendall 1975), which are advisable for such type parameters. Based on these coefficients and after their values were reduced to a scale with a maximum value of 5, as defined by the DRASTIC model, the new weighting factors were calculated. In the case where one of the coefficients is not statistically significant, the corresponding parameter will be excluded from the equation of the vulnerability. In this way, one of the drawbacks of the DRASTIC model is reversed, namely that the weight of the parameters that are important for the vulnerability is downgraded when a large number of parameters exist. Table 2 shows the correlation coefficients values and the revised weighting factors, where it becomes evident that the "soil type" and "hydraulic conductivity" parameters are not statistically significant and should be excluded. It is also seen that the largest modified weighting factor is attributed to the "aquifer type" parameter, while the "depth to groundwater" and "impact of the vadose zone" are degraded with respect to the initials ones, although they remain relatively high.

The discovery of an insignificant correlation between "nitrate concentration" and "soil type" reveals that the topsoil does not influence the nitrates concentration of the groundwater in the study area. The same conclusion is also reported by other researchers (McLay et al. 2001; Lambrakis et al. 2004), and it is attributed to the absence of reduction reactions in the soil zone due to oxygen excess.

The insignificant correlation between "nitrates concentration" and "hydraulic conductivity" respectively reveals that the aquifer hydraulic conductivity fluctuations do not influence the nitrates concentration in the groundwater. Other researchers have also expressed doubts concerning the use of this parameter for the determination of aquifer vulnerability, putting forward as a main argument the fact that this parameter is not directly connected with the alteration processes of the substances dissolved in the groundwater such as adsorption, cation-exchange and redox reactions.

After the application of the revised weighting factors and the removal of the two non-correlated parameters, Eq. (1) can be formulated as follows:

$$V_{(\text{intrinsic})} = 3 \cdot D + R + 5 \cdot A + 2 \cdot T + 2.5 \cdot I \qquad (2)$$

where $V_{\text{intrinsic}}$ is the intrinsic vulnerability, D is the depth to groundwater, R is the recharge, A is the aquifer type, T is the topography and I is the impact of the vadose zone.

With the application of the above equation, the correlation between vulnerability and nitrates concentration values is further increased, since the correlation coefficient is now $r = 0.79$ (Fig. 10), while the removal of the two parameters has slightly changed the scale of the vulnerability values, with the maximum values for the intrinsic vulnerability being lower than 160 (Fig. 11).

Addition of the contaminant loading parameter: pollution risk determination

The original DRASTIC model application as well as modifications of the method, are related to the intrinsic vulnerability calculation, which is the most important

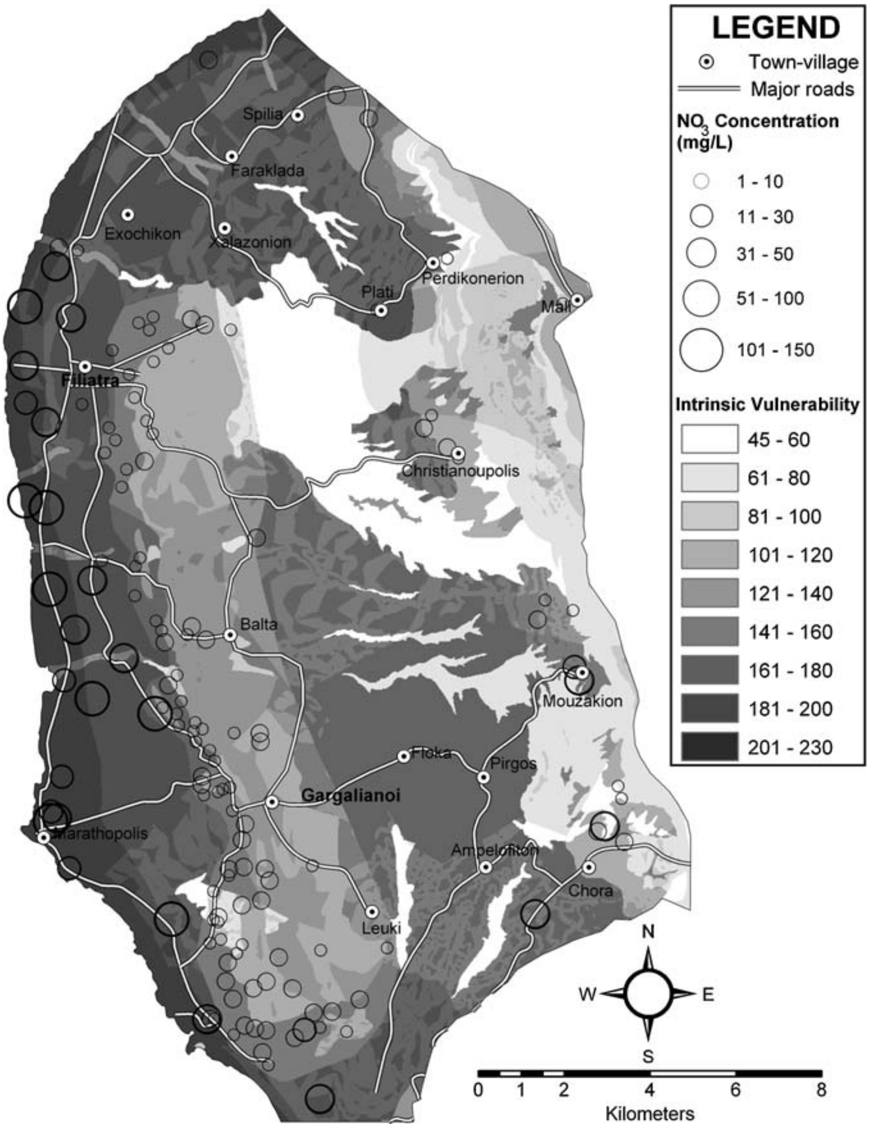


Fig. 9 Distribution of modified (modified factor ratings) DRASTIC intrinsic vulnerability and nitrates concentrations for the study area

factor affecting the nitrates concentration in the groundwater. However, as mentioned before, the contaminant loading applied to the ground surface of the research area, has a major impact upon the nitrates concentration of the groundwater, and combined with the intrinsic vulnerability, constitutes the specific vulnerability or pollution risk of the aquifer. For the calculation of this quantity, one more factor should be added to Eq. (2) in order to express the contaminant loading in each point of the research area. In this paper, it was decided to use land use as a surrogate variable for the contaminant loading parameter. The Corine Land Cover programme determines the land use distribution (Bossard et al. 2000). The initial land use distribution estimation has been improved considerably, following the corrections applied by studying the large-scale aerial photographs of Trifilia (1:30000), as well as by in situ mapping of the

Table 2 Original and modified weights of the DRASTIC factors and correlation coefficients between DRASTIC factors and nitrates concentration

Drastic factors	Original weight	Spearman's rho coefficient	Kendall's tau coefficient	Modified factor weight
Depth to groundwater	5	0.46*	0.37*	3
Recharge	4	0.14*	0.12*	1
Aquifer type	3	0.74*	0.61*	5
Soil type	2	0.11	0.08	–
Topography	1	0.29*	0.22*	2
Impact of the vadose zone	5	0.34*	0.28*	2.5
Hydraulic conductivity	3	−0.01	−0.01	–

*$p < 0.05$ where p is the statistical significance level

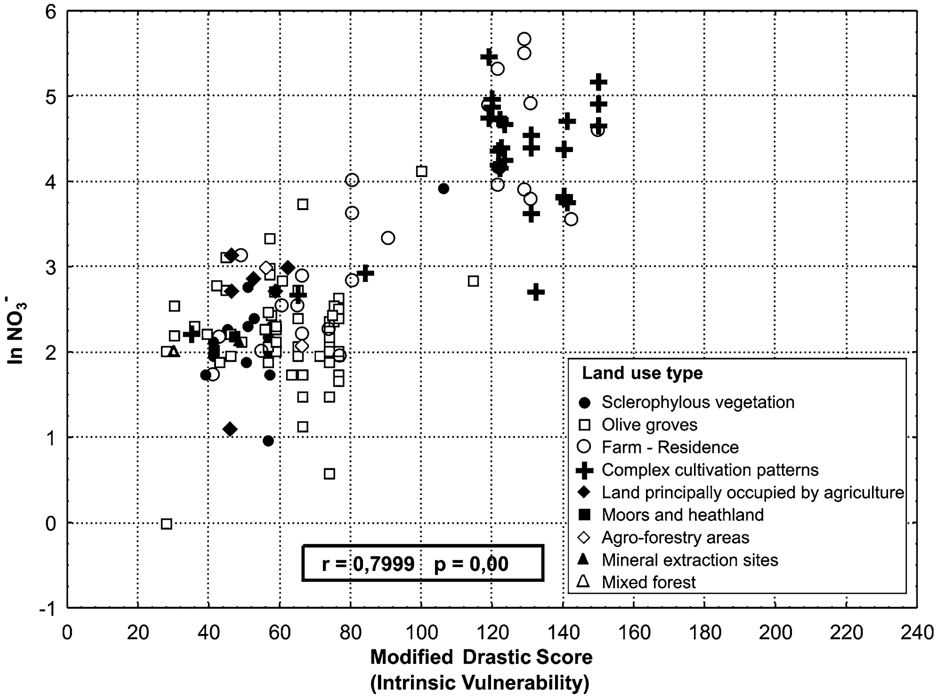


Fig. 10 Relationship of modified (modified factor ratings and factor weights) DRASTIC intrinsic vulnerability index and groundwater nitrates concentration (logarithmically transformed) for the study area

individual residences and farms, which are not included in the ‘continuous urban fabric’ and ‘discontinuous urban fabric’ land use classes of the Corine program, due to the small-scale of impress (1:100000). The combination of the above data produces the land use map of Fig. 12. The grade of each land-use category, initially derived from the literature (Secunda et al. 1998; Rupert 1999; McLay et al. 2001), was then modified similarly in accordance with the revision of the rating scales of the DRASTIC parameters. Namely, the mean nitrates concentration in each land-use category was used, reduced to a ten-grade scale, in order to produce the revised grade. The original (typical), as well as the modified/revised grades of each land-use category are presented in Table 3. The box plot diagram of Fig. 13 displays the nitrates distribution characteristics for each land use category.

The relative weight of the land-use factor will be the highest possible, namely 5, owing to the important role the contaminant loading plays in the nitrates concentration determination of the groundwater (Carter et al. 1987; Ostry et al. 1987; Vbra and Zaporozec 1994; Rupert 1998; Secunda et al. 1998; McLay et al. 2001). The selection of the highest weighting factor is enhanced by the relatively high correlation indexes between the land-use grades and the nitrates concentration (Spearman’s rho = 0.70; Kendall tau = 0.55), in accordance with the respective “aquifer type” levels (Table 2).

With the addition of the new parameter, Eq. (3) now expresses the specific vulnerability of the aquifers, such as:

$$V_{\text{specific}} = \text{Aquifer Pollution Risk} = 3 \cdot D + R + 5 \cdot A + 2 \cdot T + 2.5 \cdot I + 5 \cdot L \tag{3}$$

where V_{specific} is the specific vulnerability, D is the depth to groundwater, R is the recharge, A is the aquifer type, T is the topography, I is the impact of the vadose zone and L is the contaminant loading per land use category.

The new specific vulnerability or pollution risk map which results from the application of the above equation is presented in Fig. 14. Figure 15 illustrates the correlation between specific vulnerability and nitrates concentration with a correlation coefficient $r = 0.82$.

The improvement of the correlation, induced by the addition of the contaminant loading factor, is in the order of 0.018, which is lower than expected, based on the assumed importance of this parameter. This can be attributed to the fact that in the study area, the points with a high intrinsic vulnerability also have high contaminant loadings. The points with intrinsic vulnerability higher than 120 belong exclusively to the ‘complex cultivation patterns’ and ‘farm-residence’ land-use categories (Fig. 15). If the intrinsic vulnerability and contaminant loading relation was the reverse, the effect of the specific factor upon the increase of the correlation between pollution risk and nitrates concentration would be more decisive, as is noted by other researchers as well (Rupert 1998; Secunda et al. 1998).

The aforementioned small improvement following the introduction of contaminant loading raises the question of whether it would be effective in the calibration of this factor to consider the land use of every individual point or whether it would be better to use the land-use distribution in a buffer area around each point (Kolpin 1997; McLay et al. 2001).

The shape and extent of this area can be arbitrarily selected and kept constant in the entire study area or can be selected according to hydrogeological criteria, as the

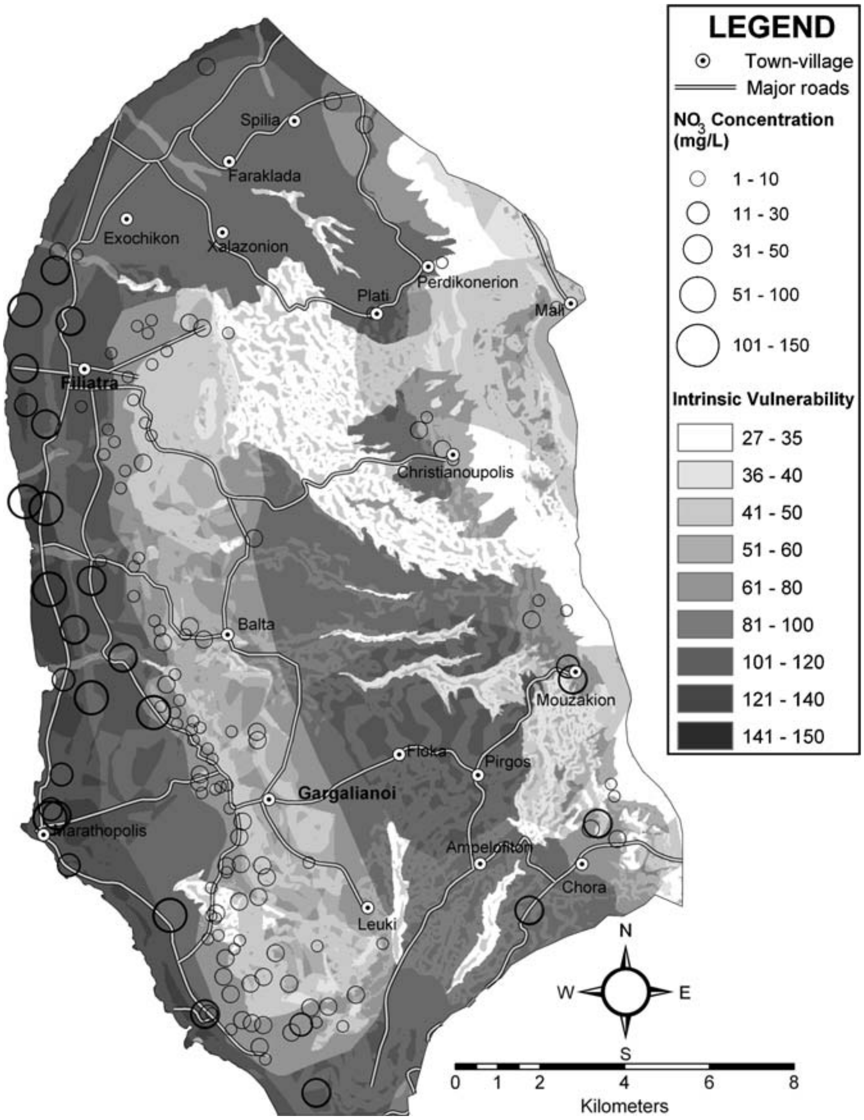


Fig. 11 Distribution of modified (modified factor ratings and factor weights) DRASTIC intrinsic vulnerability and nitrates concentrations for the study area

capture zone and groundwater flow direction, which vary at each point within the research area and can be defined only for the wells, boreholes and springs of the aquifers.

In this study, both possibilities were examined. To obtain the final rating of each point, the spatial mean rating was used, which resulted from a measure of the extent that the various land-use categories have within the buffer area and multiplied by the correspondent rating of each category as defined in the previous paragraph. This technique is automatically applied utilizing a GIS system via the application of neighbourhood spatial mean procedure upon the land-use ratings grid. For the case of the arbitrarily selected area, a circular entity with a radius of 300 m was used. Defining the buffer radius is an important consideration. If the radius is too large, the land in the perimeter of that buffer contributes proportionally less water to the bore, while in small buffer areas the risk of misclassification of land use is high (Barringer et al. 1990). Various buffer radii have been proposed from time to time with a range from 200 to 2,000 m (Barringer et al. 1990; Eckhardt and Stackelberg 1995; Kolpin 1997; McLay et al. 2001). The radius adopted for the study area has been selected upon the observations of the aforementioned researchers' remarks as well as on the basis of the hydrogeological setting of Trifilia.

Therefore, by calculating the value of L in Eq. (3) using the spatial mean of land-use ratings for a circular area of a 300 m radius, the 'neighbourhood spatial mean pollution risk' (A_{PRNSM}) is acquired. The correlation between A_{PRNSM} and nitrates concentration values is delineated in the scatter diagram of Fig. 16, presenting a correlation coefficient of $r = 0.83$. A small improvement in the correlation coefficient is observed in regard to the applied method for the point land-use rating, thus proving the correctness of the buffer area usage in the land-use rating evaluation for each point.

For the assessment of the buffer area according to hydrogeological criteria, the simple circular-shaped method delineates the wellhead area of each water sampling point

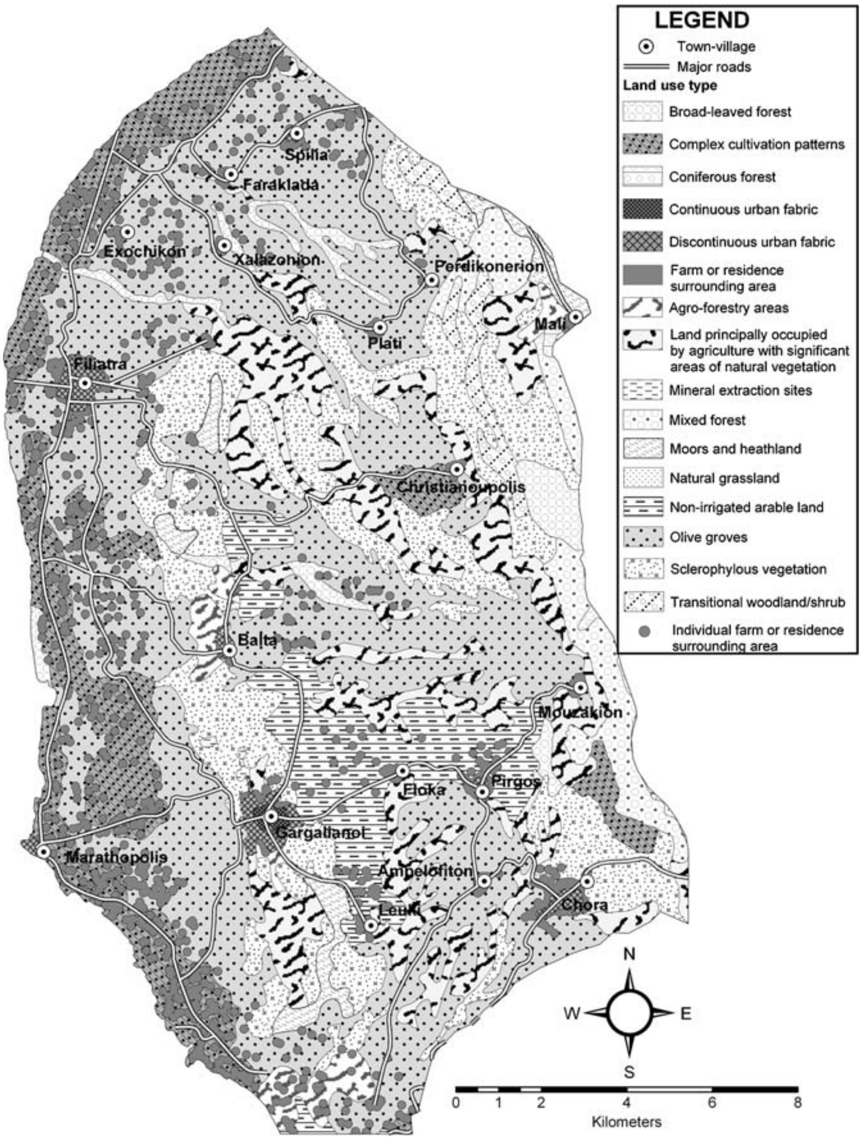


Fig. 12 Land use map of the study area

using the calculated fixed radius volumetric equation (US EPA 1994):

$$r = \sqrt{\frac{Q \cdot t}{\pi \cdot n \cdot H}} \tag{4}$$

where r is the radius of the circle, Q is the pumping rate of the well, t is the travel time for which volume is being calculated, n is the porosity and H is the length of the well screen, namely the saturated thickness of the aquifer for full penetrating wells.

The buffer area could be evaluated with more accurate methods such as the groundwater flow and contaminant's diffusion models. However, these methods require a large data set, which is very difficult and time consuming to obtain in extensive regions. Thus, such a procedure would negate the basic advantages of the pollution-risk evaluation method, which are the simplicity and ease of application.

Applying Eq. (4) to all of the 145 sampling points, the buffer area of each water point is delineated. The buffer area radius varies from 10 to 2,250 m. For each of these areas, the spatial mean of land-use rating for each sampling point is calculated using the zonal mean process in the land-use rating grid via a GIS function. The 'zonal spatial mean pollution risk' (A_{PRZSM}) is defined by applying this spatial mean for the L parameter evaluation in Eq. (3). The correlation between A_{PRZSM} and nitrates concentration values is exhibited in the scatter diagram of Fig. 17 and has a correlation coefficient of $r = 0.84$. It is ascertained that the use of Eq. (4) in the buffer area for the assessment of every sampling point, brings about a slight improvement in the correlation coefficient in regard to the arbitrarily selected circular area, common for all the water points of Trifilia. This fact proves that the buffer area definition by hydrogeological criteria is better than an arbitrary selection. On the other hand, this method cannot be applied in the whole study area and therefore it is concluded that the

Table 3 Typical and modified land use ratings

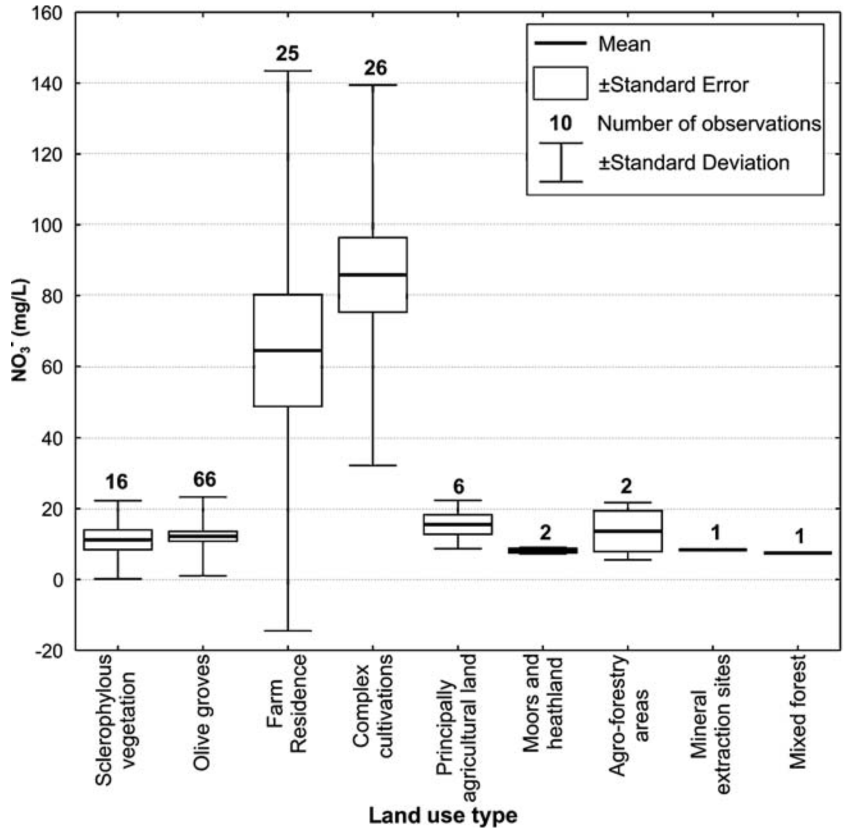
Land use type	Typical rating[a]	Mean NO_3^- concentration (mg/L)	Modified rating
Complex cultivations	10	85.8	10
Farm–residence	10	64.5	7.5
Principally agricultural land	4	15.5	4
Agro-forestry areas	3	13.6	3.5
Olive groves	5	12.2	3
Sclerophylous vegetation	1	11.2	2
Mineral extraction sites	2	8.4	1
Moors and heathland	2	8.1	1
Mixed forest	1	7.5	1
Broad-leaved forest	1	–	–
Coniferous forest	1	–	–
Continuous urban fabric	10	–	–
Discontinuous urban fabric	9	–	–
Natural grassland	3	–	–
Non-irrigated arable land	4	–	–
Transitional woodland/shrub	2	–	–

[a] Based on bibliographic references from similar studies

arbitrarily selected method is adequately functional in the pollution risk assessment of Trifilia.

Table 4 summarizes all the intrinsic vulnerability and pollution risk correlation coefficients, resulting from the modification and optimization process of the DRASTIC method through the use of hyrochemical data. A progressive improvement in the precision of determining the intrinsic and specific vulnerability is accomplished, as expressed by Pearson's (r) correlation coefficient. This improvement mainly concerns the intrinsic vulnerability, where, after modifying the original method, both in the factor ratings as well as in the factor weightings, an increase in the correlation in the order of 29.4% is achieved. The addition of the contaminant loading induces a relatively slight but important improvement at the order of 3.17%, as long as the spatial mean land use rating is used, as evaluated by the land-use calibration based on its nitrates concentration. In such a way, a correlation coefficient of $r = 0.8316$ is accomplished, showing that the pollution risk assessment by the proposed methodology adequately reflects the existing

Fig. 13 Box plot showing the distribution of groundwater nitrates concentration for the land use types of the study area



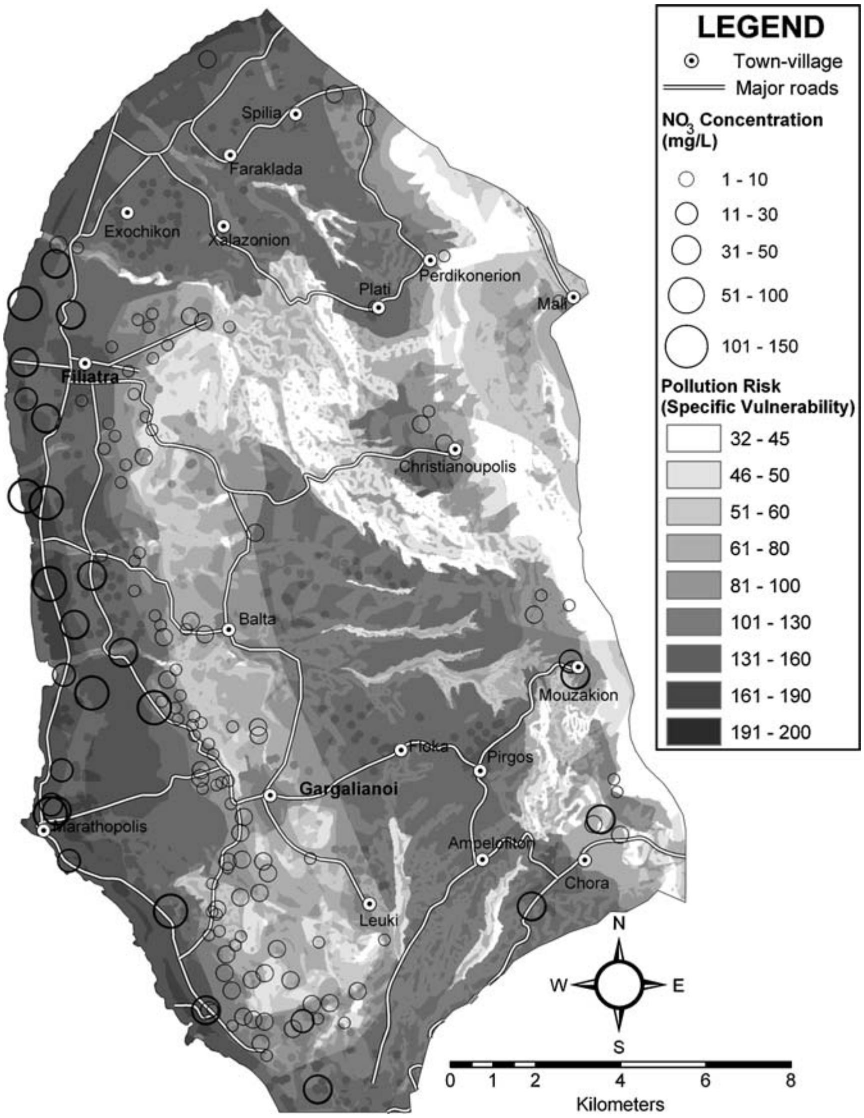


Fig. 14 Distribution of groundwater pollution risk (specific vulnerability) for the study area

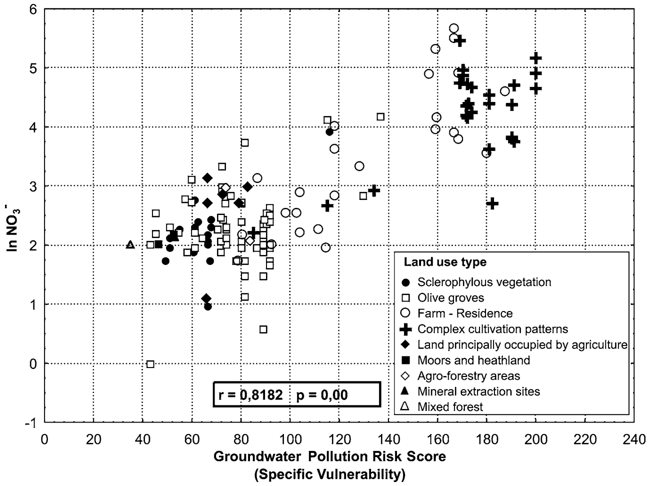


Fig. 15 Relationship of groundwater pollution risk (specific vulnerability) and groundwater nitrates concentration (logarithmically transformed) for the study area

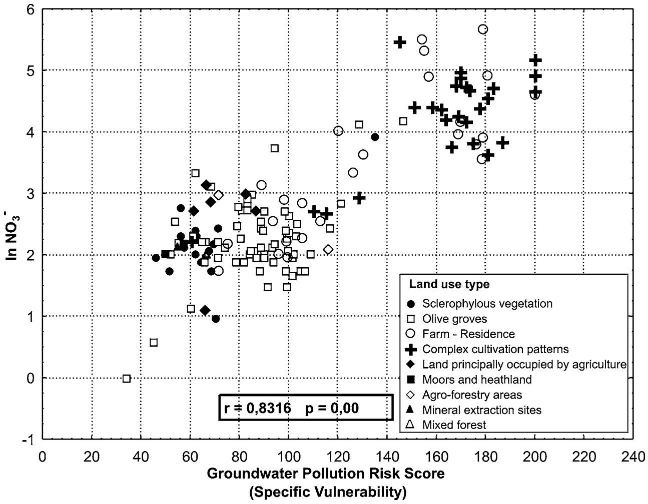


Fig. 16 Relationship of 'neighbourhood spatial mean groundwater pollution risk' A_{PRNSM}, (specific vulnerability) and groundwater nitrate concentration (logarithmically transformed) for the study area

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Table 4 Correlation coefficients for the original DRASTIC and the various modified models and corresponding correlation improvement

Vulnerability model definition	Pearson's (r) correlation factor	Step correlation improvement (%)	Overall correlation improvement (%)
$V_{intrinsic}$ (original DRASTIC model)[a]	0.5059	–	–
$V_{intrinsic}$ (DRASTIC model, modified factor ratings)	0.6808	17.49	17.49
$V_{intrinsic}$ (DRASTIC model, modified factor ratings and factor weights)	0.7999	11.91	29.4
$V_{specific}$ = pollution risk (typical land use ratings[b])	0.8051	0.52	29.92
$V_{specific}$ = pollution risk (modified land use ratings)	0.8182	1.31	31.23
$V_{specific}$ = pollution risk (neighborhood spatial mean of modified land use ratings. Fixed 300 m radius)	0.8316	1.34	32.57
$V_{specific}$ = pollution risk (zonal spatial mean of modified land use ratings. Variable radius[c])	0.8426	1.1	33.67

[a] Aller et al. (1987)

[b] Based on bibliographic references from similar studies

[c] US EPA (1994)

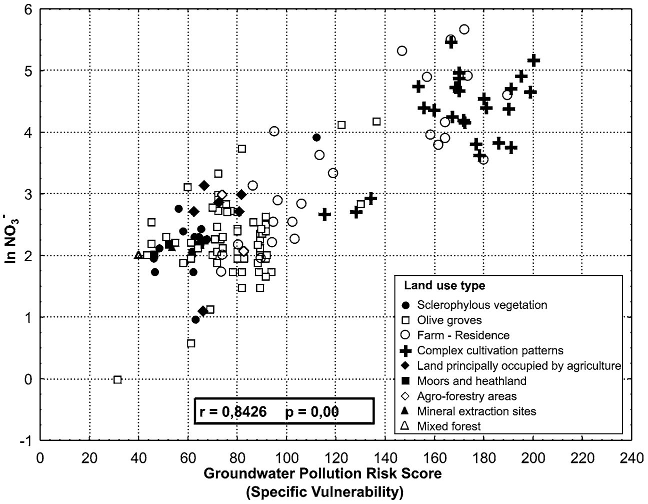

Fig. 17 Relationship of 'zonal spatial mean groundwater pollution risk' A_{PRZSM}, (specific vulnerability) and groundwater nitrates concentration (logarithmically transformed) for the study area

pollution state of the aquifers as is expressed by the nitrates distribution in the groundwater.

Discussion and conclusions

The DRASTIC method, even though it gives relatively satisfactory results in the evaluation of groundwater intrinsic vulnerability to pollution, cannot be used for the accurate assessment of the groundwater pollution risk in the study area as it is usually expressed (by the correlation between groundwater intrinsic vulnerability and nitrates concentration).

It is to this end that the DRASTIC method was employed while effecting some modifications upon the factor ratings and weightings, following an optimization procedure using nitrates concentration data. The aforementioned optimization procedure can be easily achieved using some simple statistical parameters on existing data for the majority of regions; in case the latter are not readily available, they are still relatively easy to obtain. Some of the factors that are taken into account for the vulnerability evaluation by the DRASTIC method, such as hydraulic conductivity and soil type, do not seem to be related to the nitrates concentration. This fact, combined with other authors' findings (Rosen 1994; McLay et al. 2001; Lambrakis et al. 2004) raises doubts about the use of these factors for aquifer vulnerability assessment.

The addition of the contaminant loadings to the evaluation equation of the groundwater vulnerability using the DRASTIC method, on the basis of the land use distribution, leads to the specific vulnerability or pollution risk assessment and improves the correlation between vulnerability and nitrates concentration, especially if, instead of the point land use, one takes into account the total land uses in a buffer area around each point, which can be arbitrarily or hydrogeologically defined.

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