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Research Paper

Groundwater intrinsic vulnerability assessment through GIS-based drastic method optimization in Atalanti alluvial basin, Central Greece

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ABSTRACT

The objective of this study is to estimate the groundwater intrinsic vulnerability in Atalanti porous aquifer in Central Greece in order to improve the decision making processes to prevent contamination through watershed management and land use planning. Several land areas are more susceptible to groundwater contamination than others due to geological and hydrogeological parameters controlling the pollution. Vulnerability assessment is one of the major techniques used to assist the development of protection strategies. It allows delimitation of areas with different degree of natural protection of groundwater against pollution. DRASTIC model through hydrogeological, hydraulic and soil parameters shows areas vulnerable to pollution with the help of GIS. These rated as well as weighted parameters are combined to create the final map, while results' optimization with groundwater quality data (nitrate concentration as a modifying parameter) is implemented in order to minimize the method's uncertainty by examining the sensitivity analysis. By overlying various spatially referenced data layers, the final map indicates the groundwater vulnerability to pollution across Atalanti alluvial basin. The obtained vulnerability map gives locations which must have high priority in terms of protection and pollution prevention. Finally, the proposed method is suggested for agricultural areas with similar geological, hydrogeological and land use settings.

Key words: Porous aquifer, groundwater contamination, nitrate concentration, method's uncertainty, pollution prevention, DRASTIC parameterization optimization.

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INTRODUCTION

Aquifer protection and pollution prevention is necessary for a rational and sustainable use of groundwater resources as well as for decision-policy making and action plans. The groundwater degradation of coastal aquifers, observed during the last decades, is associated with seawater intrusion, industrial urbanization and intensive agriculture. The high values in nitrates are related with human activities, intensive agriculture which is the main source of nitrate pollution, farms and uncontrolled urban waste disposal (Almasri, 2007; Almasri and Kaluarachchi, 2007; Almasri, 2008; Antonakos and Lambrakis, 2000; Voudouris et al., 2004). Agricultural areas which are intensively contaminated due to excessive use of fertilizers and pesticides are in great danger if no protection measures are taken. Several geological – hydrogeological and land use parameters need to be assessed in order to depict those areas that are at risk as far as the groundwater pollution is concerned. All spatial attributes are used so as to produce a final index, defining the groundwater vulnerability. Moreover, with the help of groundwater vulnerability maps, it is highly possible to protect the groundwater quality and prevent pollution because of the intensive human activities (Voudouris et al., 2010). Finally, the resulting intrinsic vulnerability map through GIS-based DRASTIC model (after modifying weights and rates) is optimized against groundwater nitrate concentration.

MATERIALS AND METHODS

DRASTIC methodology

DRASTIC belongs to index and overlay methods and is widely used for the groundwater risk pollution assessment based mainly on hydrogeological factors (Aller et al., 1987). DRASTIC model considers that *(a)* each pollutant is introduced from ground surface, *(b)* the pollutant is introduced to groundwater due to rain infiltration and *(c)* the pollutant's velocity is the same with groundwater's. This model takes into account seven parameters to classify the vulnerability or pollution potential of an aquifersuch as Depth to groundwater, Recharge, Aquifer type media, Soil media, Topography, Impact of the vadose zone media and hydraulic Conductivity (Figure 1a and b). Each parameter is evaluated according to a weighted rating system relevant to its importance within the model. DRASTIC Index (DI) for every hydrogeological setting is obtained by summing up the multiple of rating and the relevant weighting factor of each parameter as follows (Aller et al., 1987; Evans and Myers, 1990; Gemitzi et al., 2006; Gogu and Dassargues, 2000; Kallioras et al., 2011; Mattas et al., 2014):

$$DI = \sum_{i=1}^{7} W_i R_i = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \qquad (1)$$

$$DI = 5D_r + 4R_r + 3A_r + 2S_r + T_r + 5I_r + 3C_r$$ *(Original – initial weight values)* (2)

where W_i is the weighting coefficient with a rating value of R_i, r is the rating for each factor and w is the weighting factor. The higher the index is, the greater the aquifer's groundwater vulnerability. The land use pattern (L) having strong influence on study area's hydrogeological setting is included as the 8th parameter in the DRASTIC model. The model also includes a hydrochemical dataset (groundwater nitrate concentration) derived from the field work and chemical analyses held during the period 2004 – 2008 and 2014 – 2015. Finally, the groundwater pollution risk map is obtained by summing up the DRASTIC Index and the multiple of rating and the relevant weight factor of Land Use (Kazakis et al., 2015; Kazakis and Voudouris, 2011; Panagopoulos et al., 2006; Voudouris et al., 2010):

$$DI_{risk} = DI + L_w L_r = DI + 5L_r \qquad (3)$$

The subjectivity of the qualitative determination of both rating scale and weighting factors is the method's main weakness. However, there are worthwhile advantages such as *(a)*the method's low cost which can be implemented in large areas due to the easiness of data acquisition, *(b)* the selection and correlation of numerous parameters which reduce the likelihood of omission of any important factor enhancing the model's statistical accuracy, *(c)* the method's accuracy for large areas with complex geological structure and measurements' absence which in other cases would require the application of specialized methods and *(d)* the user's flexibility to modify, add or even decrease the weighting factors and model parameters.

Model parameters

Depth to groundwater: It is one of the most significant parameters in terms of vulnerability assessment since the groundwater depth determines the unsaturated zone thickness that a pollutant has to travel to reach the groundwater table. The shorter the route that groundwater has to travel, the less the soil materials act as filters and adsorbents. Furthermore, the shallower the water depth, the more vulnerable the aquifer is to pollution and vice versa.

Net recharge: The ground water recharge estimation should take into account all the possible aquifer's inputs such as rainfall, irrigation, artificial and lateral recharge, as well as all the outputs (evapotranspiration, surface runoff). Recharge is the principal factor for leaching and transporting contaminants. The more the recharge is, the more vulnerable the aquifer is.

(1)

Aquifer media: The aquifer's material plays important role in vulnerability assessment with respect to its ability to participate in the attenuation of the polluting load. When the ground water is hosted on rocks characterized by secondary porosity (karstic flow networks, cracks, fractures etc.), it becomes more susceptible to contamination as compared with porous formations (inter-granular porosity). The larger the grain size is and the more fractures or openings within the aquifer are, the higher the permeability and thus vulnerability of the aquifer.

(2)

Soil media: The aquifer's soil material (the upper weathered zone of ground surface) participates in pollutants attenuation processes through organic and clay materials. Consequently, sandy soils are assigned a higher rating than clay soils. Soil has a significant impact on the amount of recharge that can be infiltrated into the ground and hence on the ability of a contaminant to move vertically into the unsaturated zone.

(3)

Topography: It refers to the land surface slope, indicating whether a contaminant will runoff or remain long enough to infiltrate. When slopes are under 2%, the surface runoff velocity is quite small, thus favoring infiltration and evapotranspiration.

Impact of the vadose zone: Percolation of precipitation and any kind of surface water occur within this zone, so it

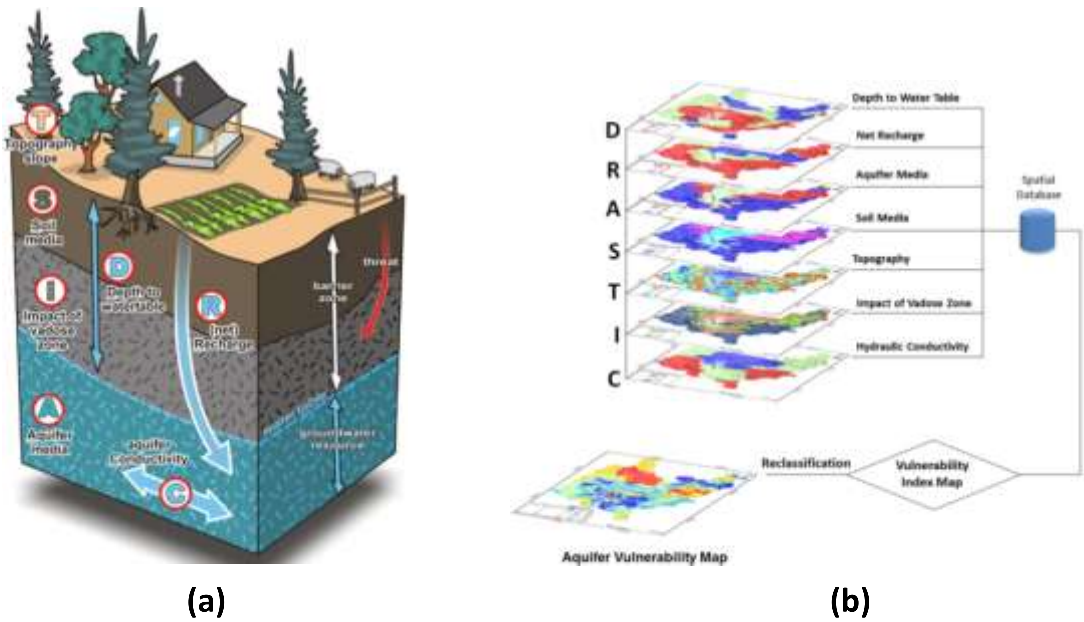


Figure 1: a)DRASTIC model's parameters (left) and b) DRASTIC map flow chart(right) (Almasri, 2007).

has an important role in attenuating the pollutant materials. Its material content (clay minerals and organic material) determines the aquifer's vulnerability which means that open fractures and karstic cavities enable a strong concentration of infiltration water, thus decreasing the vadose zone's attenuation potential.

Hydraulic conductivity: Its spatial distribution both horizontally and vertically refers to the rate at which water flows through an aquifer and the capability of the aquifer materials to transmit water. The higher the conductivity, the more vulnerable the aquifer. The results of K are derived from pumping tests and the denser the network, the more reliable its distribution within the aquifer.

Land use: This factor is co-estimated with the aforementioned seven parameters in that case in which there is an extensive and intensive residential development and rural culture for a prolonged time period which is likely to cause soil contamination and groundwater pollution due to human activities and overuse of fertilizers and pesticides. The pollutant load with the intrinsic vulnerability constitutes the aquifer's specific vulnerability or the pollution risk.

Sensitivity analysis

Based on the special geological and hydrogeological characteristics as well as the land use pattern, DRASTIC can be modified so as to include or exclude parameters (Antonakos and Lambrakis, 2007; Aschonitis et al., 2011; Panagopoulos et al., 2006). It has to be mentioned that the major method's drawback is its subjectivity in terms of parameters ratings and weighting factors. Therefore, calibration and modification of the initial algorithm have to take place in order to receive as much as possible reliable and realistic results for each study area. However, even in this case, the method still has its uncertainty but gives a clear and accurate picture of the specific areas susceptible to contamination so as to provide the appropriate and adequate instructions to the authorities for immediate intervention, if needed. Original weights and rates are modified according to the factor removal sensitivity analysis process and groundwater nitrate concentration respectively. In fact, sensitivity analysis shows the most sensitive parameter to contamination. The lowest value corresponds to the least sensitive parameter and the highest one to the most sensitive. All eight parameters are removed from the model one by one and the importance of each parameter is estimated by the mean value of each factor after removal. The modified weights can be derived by performing factor removal for all eight DRASTIC parameters and the sensitivity analysis index is calculated using the following equation (Antonakos and Lambrakis, 2007; Stigter et al., 2006):

$$S = \left(\frac{|V/N - V'/n|}{V} \right) \times 100 \tag{4}$$

where S is the index of sensitivity analysis, V is the unperturbed vulnerability index, $V'$is the perturbed vulnerability index and N, n are the numbers of data layers used to calculate V and V', respectively. In this analysis, effective weight of each parameter is compared with the theoretical one. The effective weight is a function of the value of the single parameter with regard to the other six parameters and is calculated using the following equation:

$$W = \left(\frac{P_w \cdot P_r}{V} \right) \times 100 \quad (5)$$

where W is the effective weight of each parameter, P_r is the parameter rating, P_w is the parameter weight and V is the vulnerability index.

DRASTIC model application

The DRASTIC method is applied in the porous, alluvial basin which constitutes the main aquifer in terms of surface area and pressures (intense and excessive agricultural exploitation), as well as qualitative and quantitative data adequacy with the aim to verify whether the method can be generally applied or the area's particular characteristics have an impact on the method to such an extent that cannot be successfully implemented. Apart from the standard DRASTIC method's application, calibration through sensitivity analysis and parameters' optimization is processed based on the available data, having as transformation criterion the concentration and the statistical processing of nitrates distribution (NO_3). The transformation effectiveness criterion is the correlation coefficient between the aquifer's vulnerability and the nitrate concentration. The selection of nitrates as optimization indicator is based on physico-chemical parameters prevailing across the alluvial basin and the major pollutant mainly induced in the environment by human activities because it has been proposed as a representative indicator of groundwater quality degradation and deterioration. Nitrates show significant concentration range across the study area and the sampling points are spatially distributed in areas almost covering the model parameters variation. The final goal of this study is to develop an integrated method which will be able to successfully provide the aquifer's specific vulnerability and/or the pollution risk map via land use pattern (Javadi et al., 2011; Lappas, 2018; Panagopoulos et al., 2006).

Site location – geomorphology – drainage network

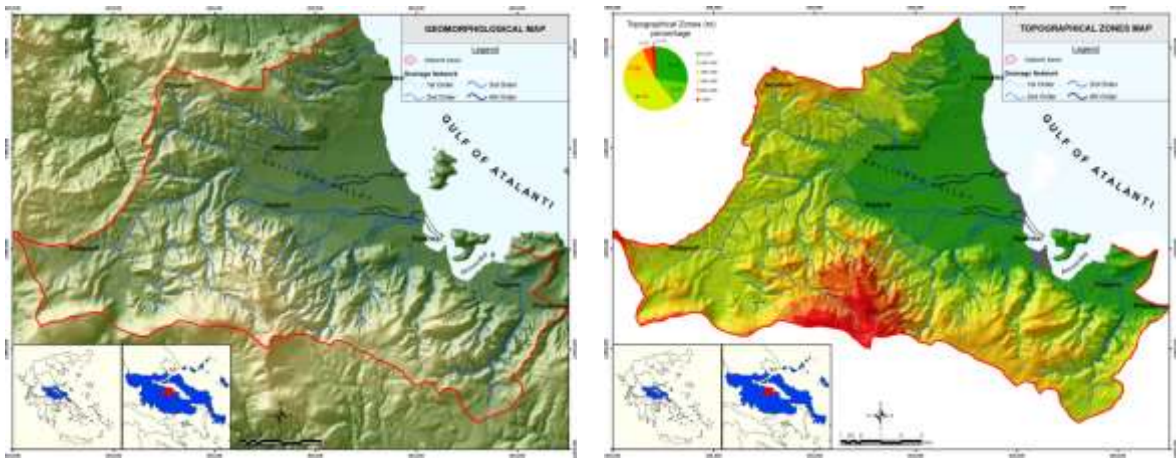
The study area is located at Eastern Central Greece at Lokrida province of Fthiotida Prefecture. The complex geomorphology of Atalanti basin area (250 Km^2 approximately) consists of areas with little or no slopes in valley where alluvial deposits are met and areas with very high and almost vertical slopes in rocky formations (Figure 2a and b). The study's area key feature is the flat surface formed somewhat above the sea level. The elevation variation between the lowest (sea level) and the highest point is approximately 663 m (South of the city of Atalanti, mount Roda). The study area is open to the sea at Northeast and is surrounded by higher or lower mountains and hilly areas (Palivos, 2001; Pavlidou, 2010). The water's erosive – weathering ability combined with the regional geology and tectonics are the main factors which form the current geomorphological conditions including both areas with mild slopes across the alluvial deposits and those with almost vertical slopes where the rocky cliffs prevail (carbonate rocks, ophiolites etc.).

Atalanti basin has a geomorphological characteristic of diverged drainage network (streams, rivers), which has length of about several kilometers, converges to the east and reaches the sea. The drainage network within the alluvial basin is regarded dense due to semi-permeable formations, while in the rocky areas, the intensive and active tectonics has formed a significantly sparse hydronetwork. Generally, the network development is mainly controlled by tectonics, thus, beingformed horizontally or vertically towards faulting zones with V-shape youth valleys as a result of the active faulting field. In any case, there is no steady river flow, but always seasonal (Alargino and Karagkiozis intermittent rivers flowing into the sea) during winter and spring (Pavlidou, 2010). The southern mountainous part of the above area has streams with very steep slopes and deep river bed, especially when passing through carbonate rocks. One of the main causes for the geomorphological setting of the study area is the water corrosion and its contribution to the weathering process. A very important factor in the above process is the intensive tectonic strain of rocks causing an extensive surface discontinuity, through which the erosion and weathering process begins (Palivos, 2001).

The region's climate belongs to the Csa type (according to Köppen classification) which is representative of the Mediterranean climate with mild wet winters and mild hot and dry summers. The average annual precipitation is 555 mm. The main features of climatic conditions in the region are the rotation period of a wet and cold season starting in October, according to precipitation and air temperatures and a dry and a hot one, starting in May. There is lack of uniformity in rainfall distribution between the lowlands and highlands with observed higher values in the mountains and lower ones in the valleys (Lappas, 2018).

Regional geological – hydrogeological settings

From a geological point of view, the study area belongs to the Subpelagonian geotectonic zone in a closed basin with post alpine deposits which have not been always communicating with the sea (Maratos, 1965). The deposits



(a) **(b)**

Figure 2: a) Geographical location, geomorphological relief (left) and b) topographical zones of Atalanti alluvial aquifer with contributing drainage area (right).

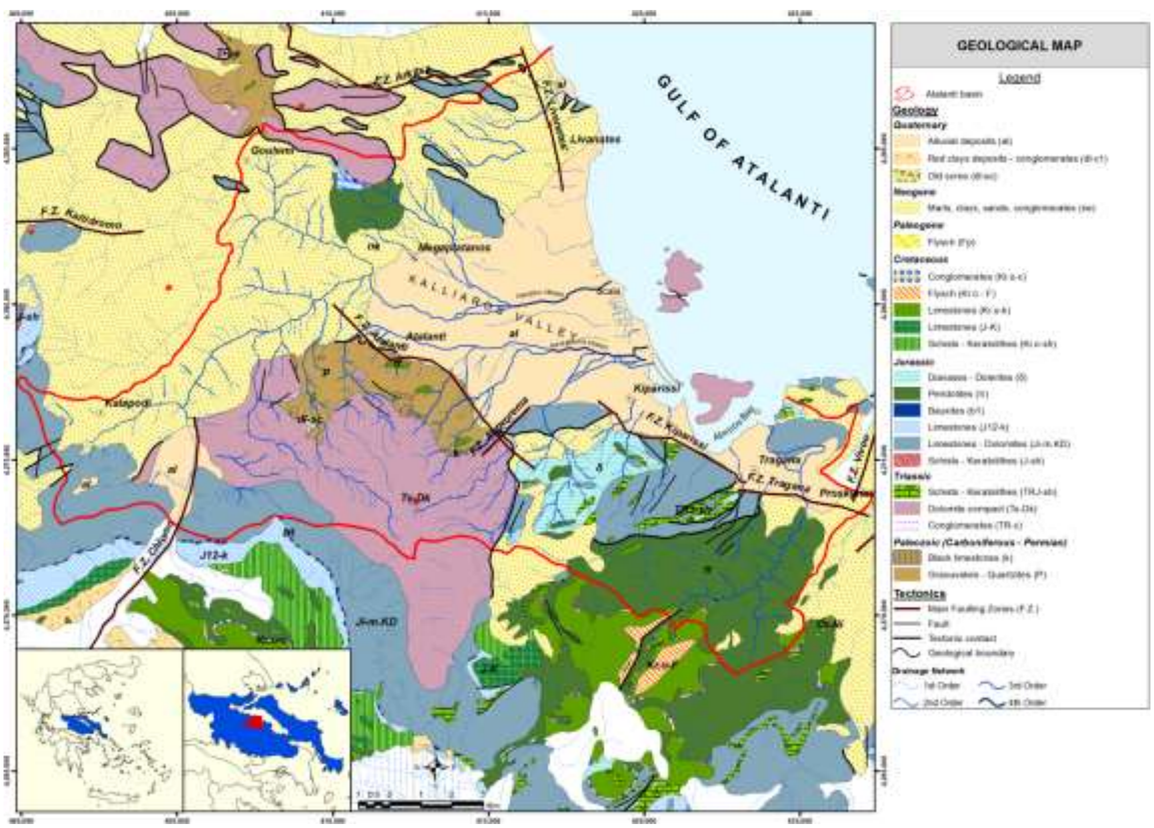


Figure 3: Regional geological map of Atalanti basin (Maratos, 1965).

emanate from the surrounding mountain range rocks. Atalanti basin consists of formations which are as follows (Figure 3): (a)Paleozoic formations consisting of shales, sandstones and conglomerates, (b)Triassic and Jurassic dolomites, limestones and ophiolitic rocks (gabbro, diabases, peridotites, serpentines), (c) Createaceous limestones and flysch, (d) Neogene sediments that are deposited after the closed basin formation consisting of marls, calcareous marls, marly limestones, clays, sandy loams, lignite and conglomerates and ***(e)***Quaternary formations that have been deposited at the lower parts of the basin with materials derived from weathering of all

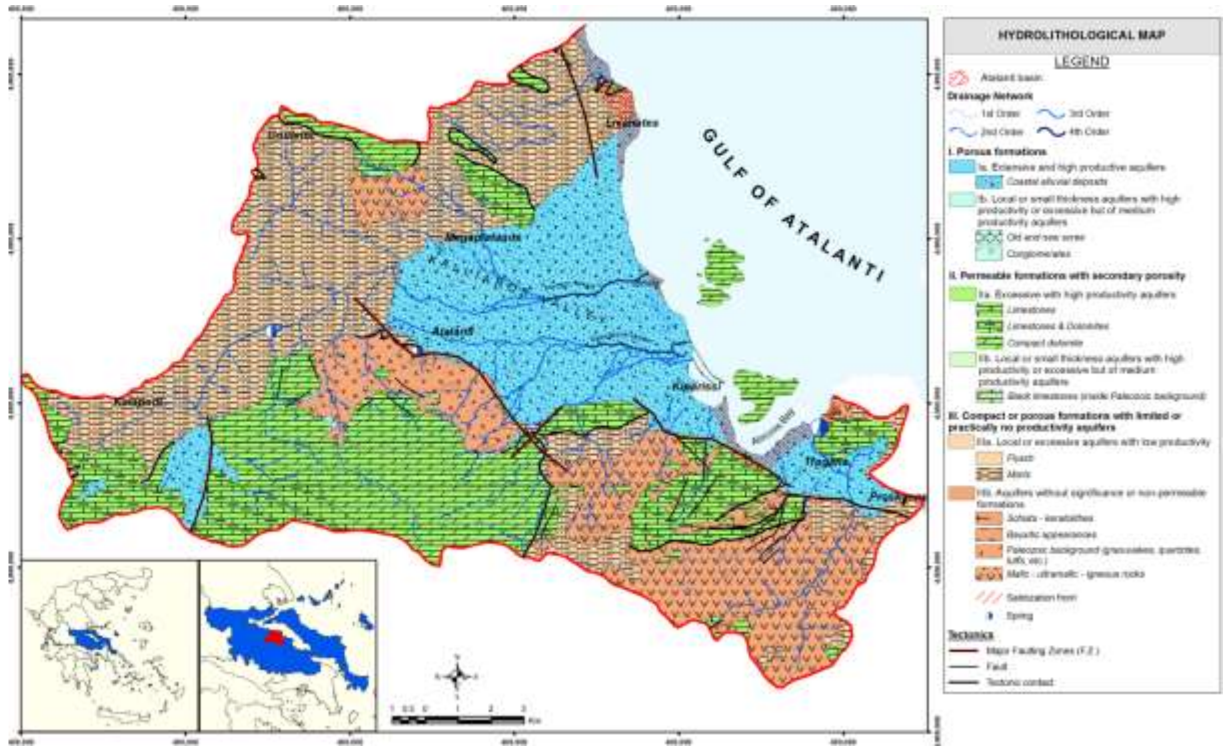


Figure 4: Hydrolithological map of the study area.

previous formations, which come across at higher topographic positions. The main feature of the geological regime during Miocene is the large-scale faults in Atalanti basin which have created many faulting zones with directions towards West-Northwest and North-Northeast (Karastathis et al., 2007).

The hydrogeological behaviour of geological formations depends on the lithological composition, degree of diagenesis and porosity. Hydrogeologically speaking, the interest area consisted of two main groups of rocks in which the groundwater flow mechanism and the storage capacity vary considerably. The first group consists of granular formations in which the hydraulic conductivity is based on the pores between the grains. The second group comprised hard basement rocks which are limestones and igneous rocks, the hydraulic conductivity of which depends on fractures, cracks, karst pipes and other discontinuities that cross their mass (Figure 4). The main aquifer is developed in carbonate rocks; on the other hand, aquifers of lower hydrocapacity are developed in the Quaternary-Neogene formations and igneous rocks. It is estimated that there is lateral communication between aquifers in carbonate rocks and the Neogene-Quaternary deposits, forming unconfined and semi-confined aquifers. Unconfined aquifers are developed in carbonate rocks as well in granular formations with large effective porosity. On the other hand, the confined aquifers are developed within Neogene formations. The alluvial deposits, due to their heterogeneity, may be considered unconfined or semi-confined aquifers. The lowland aquifer, which is intensively exploited through boreholes (approximately 650, mostly for irrigation use) is important for the economic development in the region. The depth to water table in the alluvial aquifer ranges from 1.2 to 8 6m below surface ground or from 2.2 to 47 m above sea level. Groundwater flows are mainly from the West towards East (Gulf of Atalanti).

Land use pattern

According to the European programme Corine Land Cover (2000), with the help of GIS, the whole study area is covered by 13 discrete landuse categories from which the highest percent is occupied by sclerophyllous vegetation (29.7%), another percent by non-irrigated arable land (20.5%), olive groves (16.6%) and complex cultivation patterns (11.7%), a relatively small percent by transitional woodland – shrub (9.7%) and land principally occupied by agriculture with significant areas of natural vegetation (6.9%) and finally, areas with mixed forest (2.3%), natural grasslands (1.4%) and discontinuous urban fabric (1.2%). The flat and coastal areas are intensively cultivated which causes pressures to water resources both quantitatively and qualitatively due to the uncontrolled and irrational use of fertilizers and pesticides unlike to hilly and mountainous regions which consisted of forests, and grasslands (Figure 5).

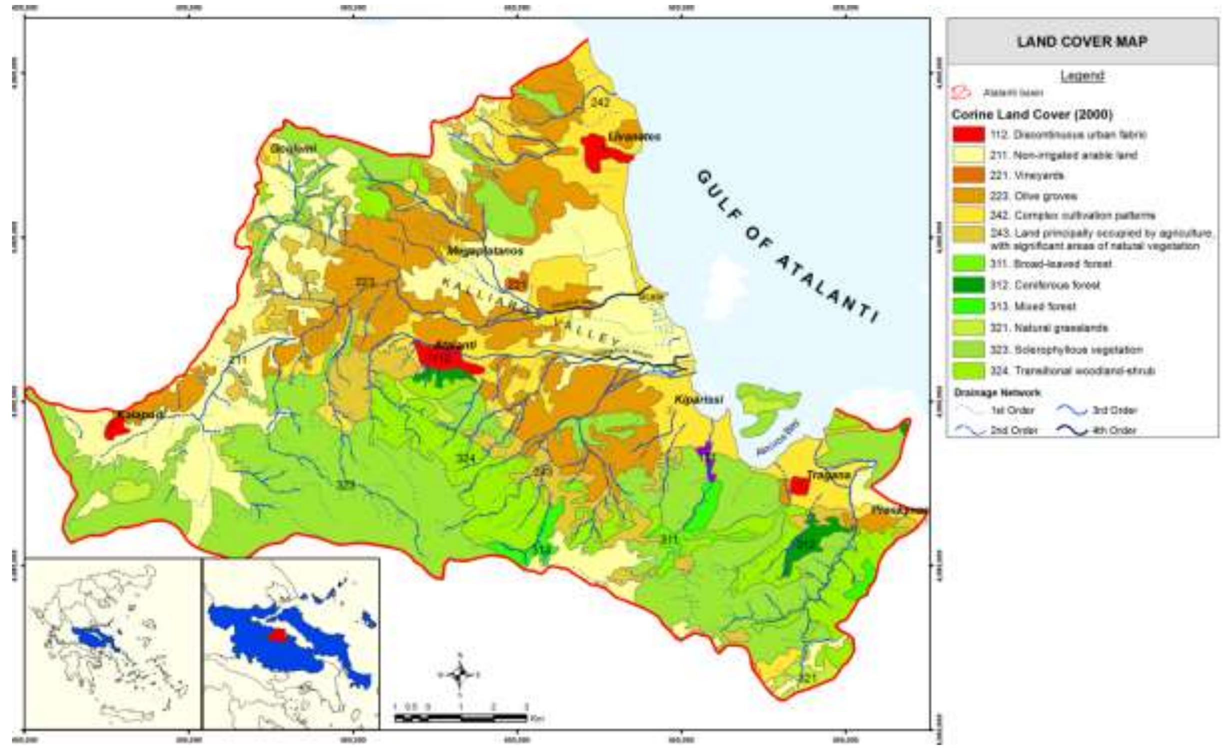


Figure 5: Land use pattern of the study area (CORINE, 2000).

Additionally, based on European network NATURA 2000, there are 3 protected regions within the study area which are Kiparissi wetland (area of 10.6k m^2, coastal shallow lagoon separated by a land stripe of 1.3 km length – GR2440001) and the small islands in the Atalanti gulf (Gaidaros and Atalantonissi), as well as the wildlife shelters of Karagkiozis – Asproyes and Tragana – Kiparissi – Kolakas.

RESULTS AND DISCUSSION

Initial model parameterization

According to the aforementioned geological – hydrogeological data and taking into account the mean groundwater depth within the alluvial deposits, the groundwater flow has a West – East direction towards the sea. As it seems the highest parameter values are observed across the coastal zone, while the lowest ones in the western hilly areas of the alluvial aquifer. Also, the net recharge ranges from 76 to 96 mm/yr with the highest values to be met at the edge of sandy-clay formations at Southwest, near to the tectonic contact between the carbonate rocks and the Quaternary deposits. Moreover, the study area consists of alluvial deposits, that is, rate 5 and weight 3 which means that the final score is 15 $(A_w x A_r)$. As far as the soil media is concerned, sandy-clay-loam prevails; therefore, the final value is 8 $(S_w x S_r)$ given that rate and weight are 4 and 2, respectively (Aller et al., 1987). Furthermore, the unsaturated zone consists of alluvial formations (sand, clays, pebbles, conglomerates, etc.) and is estimated that its texture remains the same (the final score equals to 40). Topographically speaking, the slope is considered mild (0-6%) except for the aquifer's skirts where steep slopes are met (15-60°). Finally, the hydraulic conductivity (K) has been estimated through several boreholes' pumping tests conducted within the alluvial formations (Figure 6a-d).

Taking into consideration the initial DRASTIC maps (original rates and weights), the method yields 9.1% ranking from *Moderately High* to *Extremely High* mainly in the coastal areas (Table 1). Nevertheless, when DRASTIC parameters are combined with land use pattern, the percentage increases to 23.6% which is attributed to the particularly important role of land use in terms of groundwater protection and pollution prevention. As a matter of fact, the central and western part of alluvial basin ranges from *Low* to *Extremely Low* because of the deep water level, the steeper topography and the relatively low hydraulic conductivity (Figure 7a and b).

Rates–weights evaluation and validation: Parameters removal

By applying data sensitivity analysis with parameters removal technique, one can observe that the initial weights

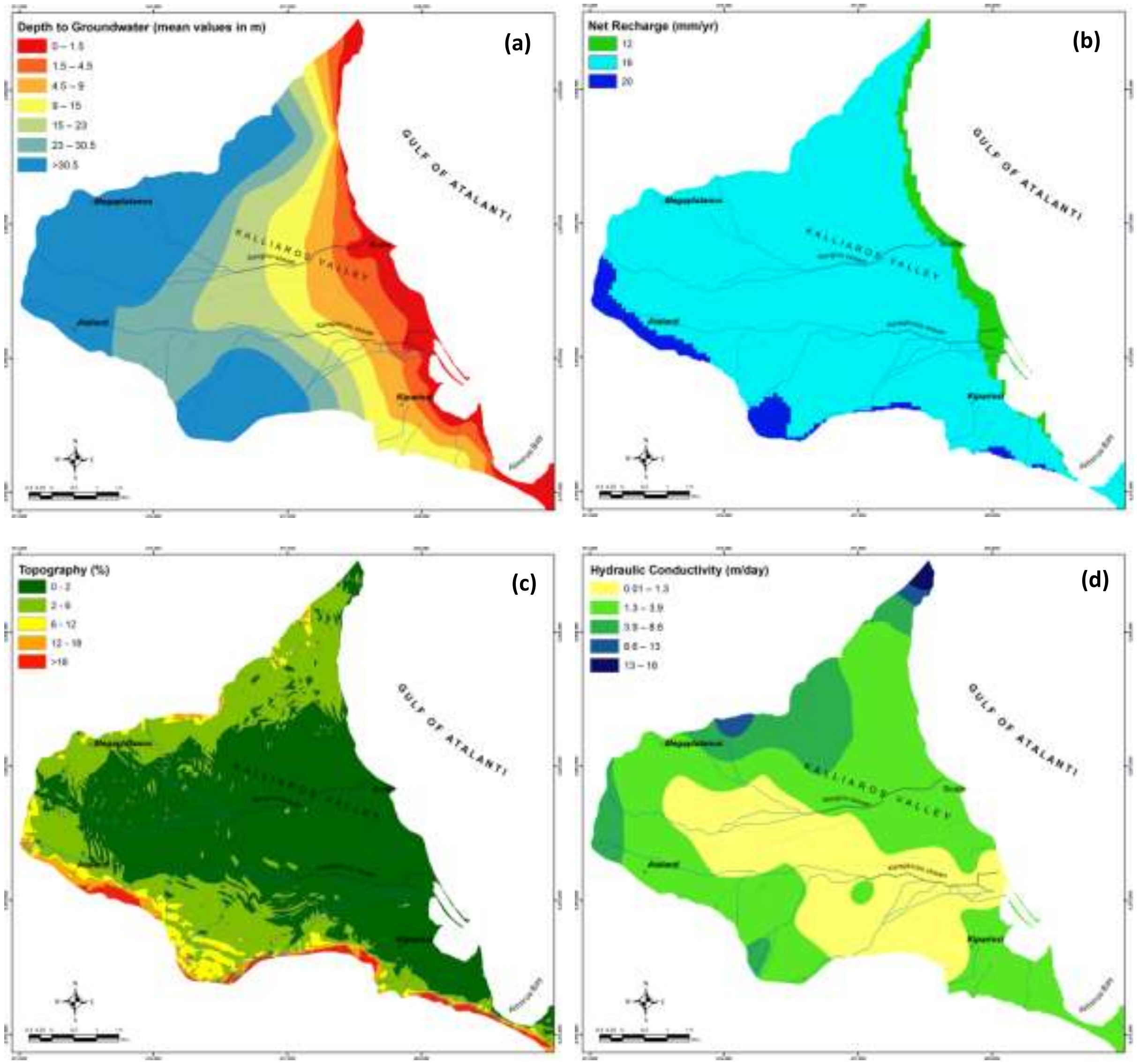


Figure6: a) Depth to Groundwater contouring map(up left), b) Net Recharge zone raster map(up right), c) Slope map based on the initial rate and weight(down left) and d) Hydraulic Conductivity map derived by the initial rate and weight (down right).

Table 1: DRASTIC index ranges with and without land use (LU) parameter.

DRASTIC classes	DRASTIC range	DRASTIC area (km^2)	DRASTIC area (%)	DRASTIC range-LU	DRASTIC area-LU (km^2)	DRASTIC area-LU (%)
Extremely low	92 – 99	12.6	23.2	93 – 101	9.9	18.3
Very low	99 – 107	18.7	34.5	101 – 106	16.4	30.3
Low	107 – 114	4.6	8.5	106 – 112	5.0	9.2
Moderately low	114 – 122	4.3	7.9	112 – 119	4.9	9.0
Moderate	122 – 129	4.9	9.0	119 – 126	5.2	9.6
Moderately high	129 – 137	5.4	10.0	126 – 135	5.8	10.7
High	137 – 144	2.8	5.2	135 – 141	3.9	7.2
Very high	144 – 152	0.7	1.3	141 – 149	1.8	3.3
Extremely high	152 – 159	0.2	0.4	149 – 163	1.3	2.4

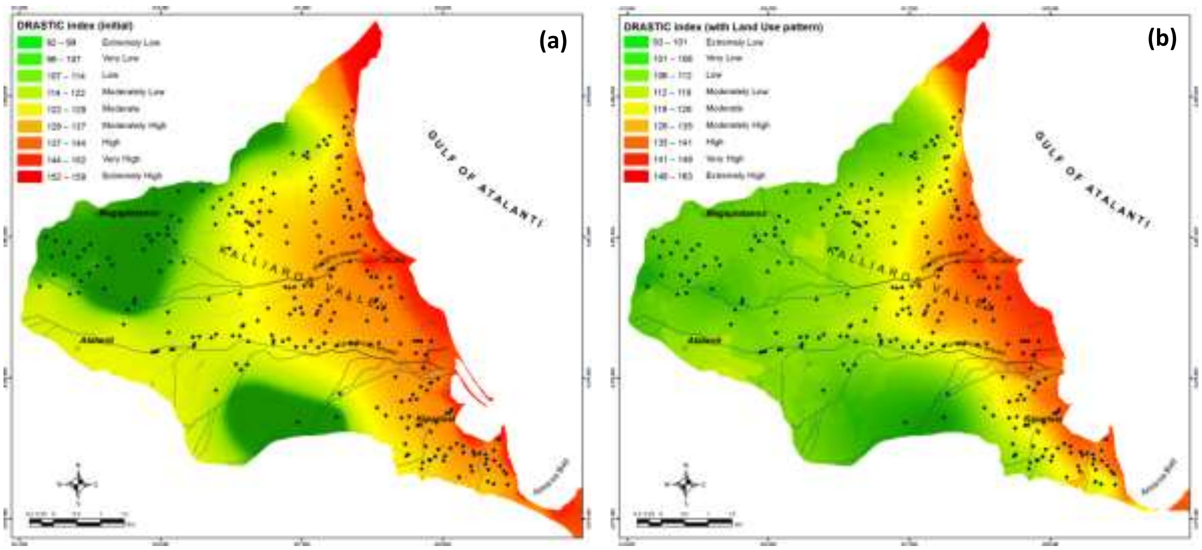


Figure 7: a) DRASTIC Index map (intrinsic groundwater vulnerability map) (left) and b) Groundwater Pollution Risk map attributed by Land Use(right).

Table 2: Statistical indices after removal parameter sensitivity analysis.

Removal parameter	D	R	A	S	T	I	C	L
Minimum	1.22	0.19	0.01	0.11	1.25	0.10	0.97	1.98
Maximum	4.68	3.25	0.07	1.09	3.71	0.55	1.96	3.88
Mean	3.02	1.96	0.03	0.30	2.61	0.22	1.58	3.21
Initial weight	5	4	3	2	1	5	3	5
Modified weight	4.71	3.12	0.05	0.53	4.14	0.35	2.56	5

should be modified due to the fact that both the study's area specific geological – hydrogeological characteristics and land use pattern form quite different conditions with those described by the equation's original weights. Therefore, by applying simple statistics (Table 2) and removing one parameter at a time, the concluding results are very useful. Given that the *Land Use* weight remains unchange, it seems that the great weighting factor is assigned to the parameter *Depth to Ground water,* while the parameters weights of *Net Recharge* and *Hydraulic Conductivity* are degraded but still relatively high, except for the parameter *Topography* which is significantly upgraded.

Thus, considering the above technique's results, the DRASTIC equation is modified as follows:

$$DI_m = 4.71D_r + 3.12R_r + 0.05A_r + 0.53S_r + 4.14T_r + 0.35I_r + 2.56C_r$$

$$DI_{risk(m)} = DI_m + L_w L_r = DI_m + 5L_r$$

By the same way, each parameter's effective weight is calculated (Table 3) in order to take into account only those parameters which play important role in the final method's results. It is therefore appropriate to remove some parameters from the original DRASTIC index equation. Hence, the parameters *Aquifer Media*, *Soil Media* as well as *Impact of the Vadose Zone* have minor impact on the final results due to the fact that the alluvial unconfined aquifer is relatively homogeneous and the unsaturated zone's material texture (sand-clay-loam) does not significantly affect the pollutants' concentration probably owing to the lack of reductive conditions (oxygen excess).

Consequently, the final modified DRASTIC index after parameters' removal is as follows:

$$DI_m = D_w D_r + R_w R_r + T_w T_r + C_w C_r = 4.71D_r + 3.12R_r + 4.14T_r + 2.56C_r$$

$$DI_{risk(m)} = DI_m + L_w L_r = DI_m + 5L_r \quad (6)$$

(7)

Method optimization

The DRASTIC optimization process is mainly based on the

Table 3: Effective weight calculation after removal parameter sensitivity analysis.

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)		
			Mean	Min	Max
D	5	21.74	20.67	12.04	30.90
R	4	17.39	14.49	8.75	23.80
A	3	13.04	5.22	2.68	12.58
S	2	8.70	8.42	2.82	11.41
T	1	4.35	18.71	8.41	26.17
I	5	21.74	6.63	2.13	12.69
C	3	13.04	12.12	4.23	18.52

Table 4: Initial and modified rating of DRASTIC method, based on mean nitrate concentration (NO_3 in mg/l).

Depth to groundwater (m)				Net Recharge (mm/yr)			
Range	Initial rating	Mean nitrate concentration	Modified rating	Range	Initial rating	Mean nitrate concentration	Modified rating
0.0-1.5	10	31.0	*6.6*	0-50	1	-	-
1.5-4.5	9	47.2	*10.0*	50-75	3	55.7	*10.0*
4.5-9.0	7			75-90	3	40.4	*7.3*
9.0-15.0	5			90-100	3	6.7	*1.2*
15.0-23.0	3			100-180	6	-	-
23.0-30.5	2	28.7	*6.1*	180-250	8	-	-
>30.5	1			>250	10	-	-

Hydraulic conductivity (m/day)				Topography (%)			
Range	Initial rating	Mean nitrate concentration	Modified rating	Range	Initial rating	Mean nitrate concentration	Modified rating
0.01-1.3	1	*43.4*	*10.0*	0-2	10	42.8	*10.0*
1.3-3.9	2			2-6	9	34.1	*8.0*
3.9-8.6	4	*22.1*	*5.1*	6-12	5	17.6	*4.1*
8.6-13.0	6			12-18	3		
13.0-24.2	8	-	-	>18	1	-	-
>24.2	10	-	-				

correlation between the vulnerability index values and mean nitrate concentration (in mg/l) obtained during the periods of 2004 – 2008 and 2014 – 2015. Pearson *(r)* correlation coefficient assumes data normal distribution which are relatively normalized ($p<0.005$), as shown by the Normal Probability Plot (Q-Q plot) (Figure 8a).

The original ratings rescaling is obtained by calculating the mean nitrate concentration to each parameters classes, as defined by the initial model. Each parameter is subjected to statistical control so as to ascertain whether the mean value of adjacent classes significantly differs. If not, the classes are grouped. Below, box plots for all the statistically different classes of all DRASTIC remaining parameters are designed. Moreover, Table 4 shows each class initial and modified ratings tiled together with the mean nitrate values. It is proved that the mean values follow the corresponding natural changes of all the arithmetical parameters (Depth to Groundwater, Net Recharge, Topography and Hydraulic Conductivity). Additionally, Land Use classes rating rescaling (Figure 8b-f) takes place by applying the same methodology as described above (Table 5).

DRASTIC model parameters modification and optimization both in weights and ratings resulted in gradual improvement of the intrinsic and specific vulnerability as expressed by Pearson coefficient (initially

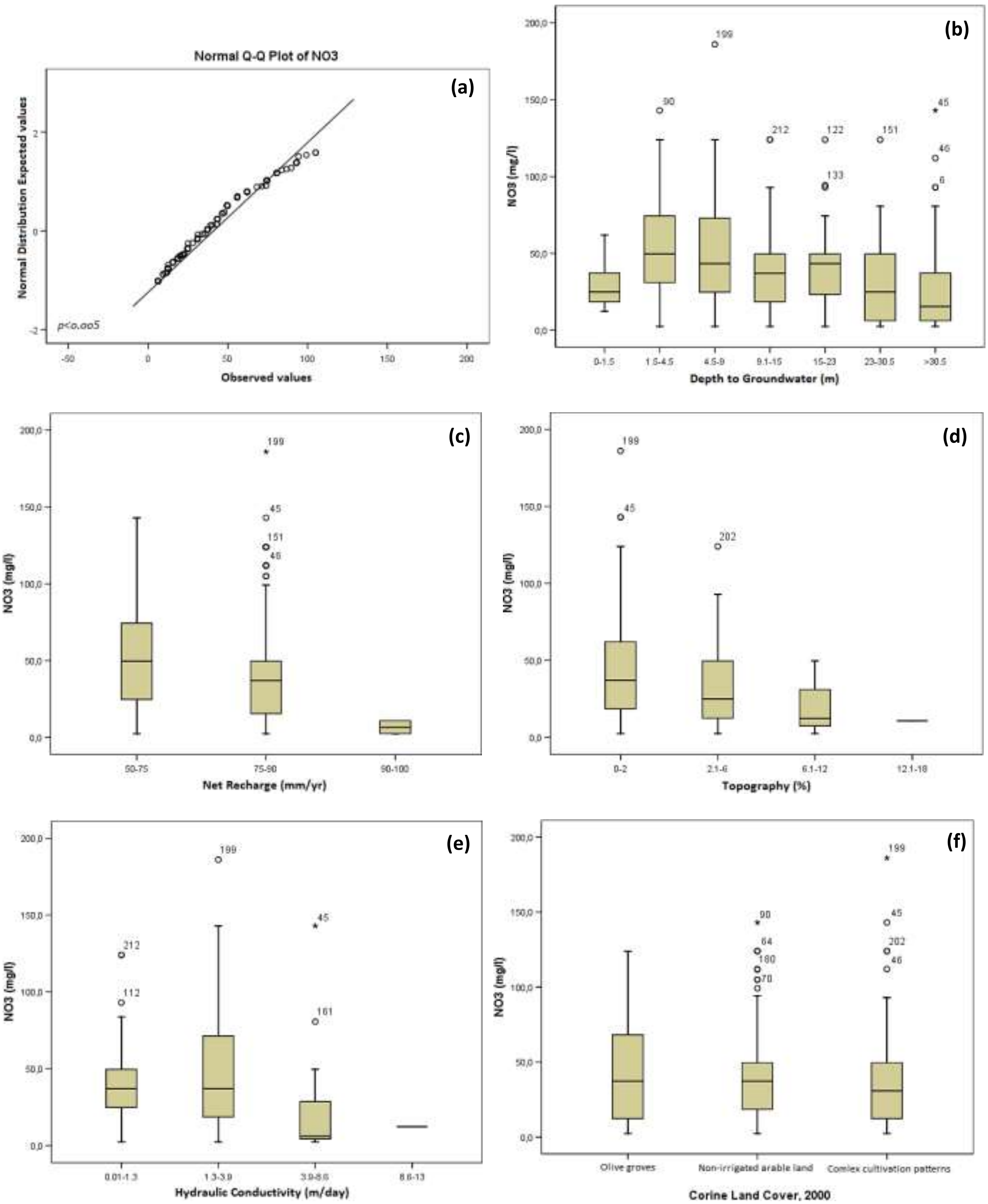


Figure 8a-f: Normal distribution of the groundwater nitrate concentration (mg/l) – Q-Q plot (up left) andBoxplots showing the nitrate distribution in each class of the DRASTIC method's parameters.

Table 5: Initial and modified rating of Land Use classes, based on mean nitrate concentration (NO_3 in mg/l).

Land use classes	Initial rating	Mean concentrationvo₃ (mg/l)	Modified rating
Sclerophyllous vegetation	1	-	1
Transitional woodland-shrub	2	-	2
Broad-leaved forest	2	-	2
Coniferous forest	2	-	2
Mixed forest	2	-	3
Natural grasslands	3	-	4
Non-irrigated arable land	3	41.1	8
Land occupied by agriculture with significant areas of natural vegetation	4	-	5
Vineyards	4	-	6
Olive groves	5	46.2	9
Discontinuous urban fabric	9	-	10
Mineral extraction sites	9	-	10
Complex cultivation patterns	10	39.8	7

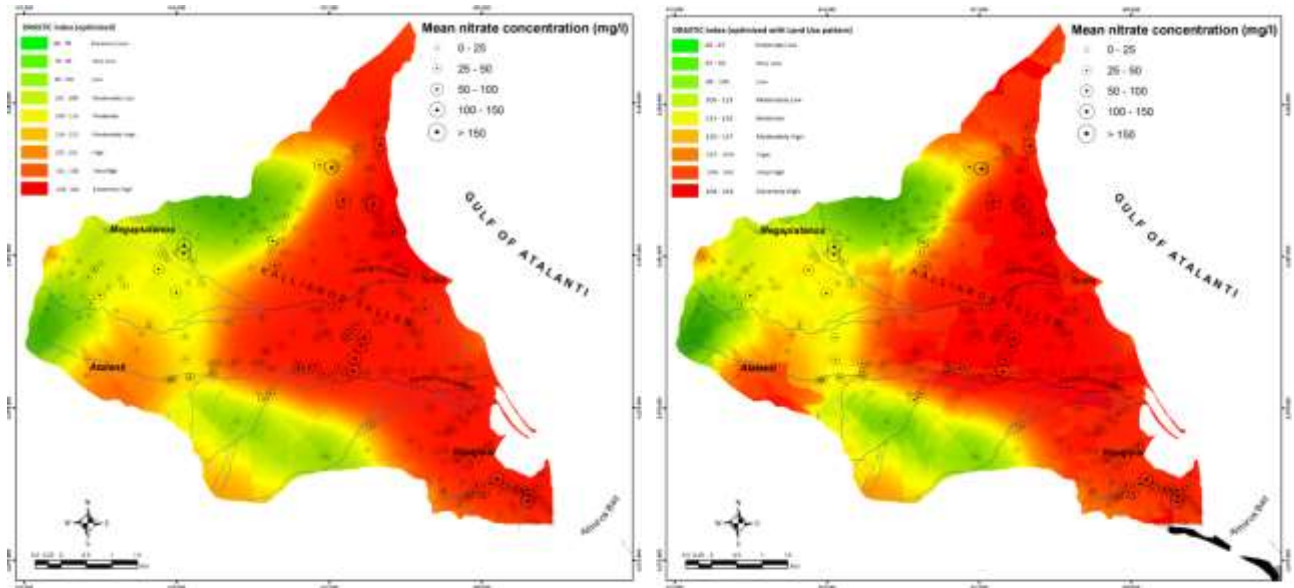
Table 6: Optimized DRASTIC index ranges with and without land use (LU) parameter.

DRASTIC classes	DRASTIC range	DRASTIC area (km^2)	DRASTIC area (%)	DRASTIC range-LU	DRASTIC area-LU (km^2)	DRASTIC area-LU(%)
Extremely low	63 – 78	0.7	1.3	66 – 87	0.6	1.1
Very low	78 – 90	1.3	2.4	87 – 96	1.3	2.4
Low	90 – 101	1.8	3.3	96 – 105	1.9	3.5
Moderately low	101 – 109	2.8	5.2	105 – 113	2.6	4.8
Moderate	109 – 116	8.9	16.4	113 – 120	8.8	16.2
Moderately high	116 – 123	9.4	17.3	120 – 127	9.6	17.7
High	123 – 131	5.4	10.0	127 – 134	5.3	9.8
Very high	131 – 138	23.2	42.8	134 – 142	20.4	37.6
Extremely high	138 – 146	0.7	1.3	142 – 151	3.7	6.8

Table 7: Correlation coefficients for the original DRASTIC and the various modified models and corresponding correlation improvement.

Vulnerability model	Pearson*(r)* correlation factor	Step correlation improvement (%)	Cummulative correlation improvement (%)
$V_{intrinsic}$ (original DRASTIC model)	0.448	-	-
$V_{intrinsic}$ (DRASTIC model, modified factor ratings)	0.512	14.3	14.3
$V_{intrinsic}$ (DRASTIC model, modified factor ratings and factorweights)	0.584	14.1	28.4
$V_{specific}$(pollution risk, typical land use ratings)	0.642	9.9	38.3
$V_{specific}$(pollution risk, modified land use ratings)	0.739	15.1	53.4

r=0.45, then r=0.58and finally, r=0.74, see Table 7). Eventually, a quite satisfactory correlation coefficient is obtained, indicating that the pollution potential assessment as proposed by the above methodology is close enough to the current aquifer's conditions. By comparing the initial and modified DRASTIC index, an aerial increase in classes *Moderately High* and *Extremely High* is observed (Table 6). This fact combined with the constantly increasing correlation coefficient suggests that the method's weights and rates modification are mandatory in order to obtain more precise, accurate as well realistic results. However, high nitrate concentration values (>50 mg/l) are still observed in areas with relatively low DRASTIC index which practically means that the excessive and irrational use of fertilizers and pesticides has affected less vulnerable to contamination regions (Figure 9a and b). Though, it has to



(a) **(b)**

Figure 9: a) Optimized Intrinsic Groundwater Vulnerability map (left) and b) Optimized Groundwater Pollution Risk map with nitrate concentration (right).

be pointed out that DRASTIC values are relevant, and case of a low index area does not necessarily mean that the aquifer is not prone to contamination, but relatively less vulnerable than other areas with higher DRASTIC index (Voudouris et al., 2010).

Conclusions

A GIS based DRASTIC model is applied for the groundwater vulnerability to pollution estimation and evaluations in Atalanti alluvial basin having first calibrate and modify the method's parameters using mean nitrate concentration. The above methodology uses the basin's topographical, hydrogeological characteristics as well as land use patterns to detect the susceptibility of the groundwater resources. DRASTIC seems to adequately assess statistically and geographically the intrinsic vulnerability related to nitrate distribution; however, it cannot be used due to the fact that each parameter's weights and rates are derived by the researchers' subjective evaluation without taking into account the particular local conditions. The optimized vulnerability map gives locations which must have high priority in terms of protection and pollution prevention. Groundwater nitrate concentration is used and evaluated for DRASTIC results' validation. High nitrate concentration represents possible nitrate enrichment in the highly vulnerable aquifer medium. Moreover, it is proved that the subjectivity of the DRASTIC parameters can be significantly decreased by an optimization process combined with sensitivity analysis and groundwater quality data. Therefore, it is necessary to calibrate and modify the original index in order to obtain more accurate results. Finally, the proposed method is suggested for agricultural areas with extensive nitrate pollution and similar geological-hydrogeological settings.

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