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Evaluation of groundwater vulnerability in a Greek island using GIS-based models

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ABSTRACT

The evaluation of groundwater vulnerability is a very important task, especially in sensitive areas such as islands where groundwater resources are scarce and often of poor quality. In the present study a geographic information systems based methodological approach is followed, considering three different models, namely the Generic DRASTIC, the Pesticide DRASTIC and the Susceptibility index (SI) in order to evaluate groundwater vulnerability in the island of Aegina, Greece. Seven parameters—depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone media and hydraulic conductivity of the aquifer (DRASTIC) along with land use changes—have been considered as weighted layers to enable an accurate mapping of groundwater contamination risk. The results indicate "high" to "very high" vulnerability to groundwater contamination along the north and the northwestern parts of Aegina island for both DRASTIC and SI models. These sensitive regions exhibit characteristics such as shallow depth to groundwater, extensive marine and alluvial deposits, highly permeable limestones, flat topography and intensive agricultural activities. The distribution of nitrate concentrations in groundwater in the study area indicated that both DRASTIC models are characterized by quite good to very good accuracy, while moderate correlation was noted for the SI model. Sensitivity analysis was also performed to assess the impact of DRASTIC and SI parameters and thus identify the most critical ones that require further future investigation. Aquifer media is the parameter that exhibited the highest impact on groundwater vulnerability indices followed by the impact of the topography and soil media. The methodology adopted in the present study can be used as a decision support tool to indicate which preventive or remedial measures need to be taken by local and regional authorities as well as by policy makers, in order to minimize the cost of groundwater monitoring and consequently improve groundwater quality and agricultural sustainability.

Keywords: Aegina island; Groundwater vulnerability; Generic DRASTIC; Pesticide DRASTIC; Susceptibility index; Sensitivity analysis

1. Introduction

Groundwater is often the only available source of water supply in small- to medium-sized islands for both urban and agricultural usage [1]. In most cases, these sensitive areas are especially vulnerable to nitrate contamination and salinity problems due to a number of factors that limit groundwater availability. These include shallow water table, highly permeable marine and alluvial deposits, interconnections between urban and agricultural land uses, and seawater intrusion due to overpumping of groundwater for irrigation [2,3].

The assessment of groundwater vulnerability to contamination through modeling is an effective tool that determines

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environmental impacts of anthropogenic activities at low cost and over a short period of time compared with traditional groundwater quality approaches [4]. It can be used to evaluate not only variations of risk over time, caused from changes of land uses, but also those derived from contaminants, such as nitrates, which migrate via preferential hydraulic flow pathways [2,5].

During the last decades, several models have been developed for assessing groundwater vulnerability using different evaluation parameters and approaches, including GOD, SINTACS and AVI [6]. Among all, the DRASTIC model, developed by the US Environmental Protection Agency (US EPA), still remains one of the most frequently used approaches for different types of aquifers. DRASTIC quantifies on a weighting basis seven parameters, namely depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity for enabling a reliable assessment of vulnerability [7,8].

Recent studies have revealed that changes of land uses are also a key parameter that has to be taken into account when predicting the effect of anthropogenic activities on groundwater resources [3,9]. Therefore, the Susceptibility index (SI), based on the DRASTIC model, has also been applied in this study to assess the effect of the land use on groundwater vulnerability in a Greek island, where land use changes pertinent mainly to tourism development and agricultural production are common. The SI model enables an in-depth and comprehensive analysis of the impacts due to continuous urban development by taking into account the shortage of land for agricultural purposes [10,11].

Both DRASTIC and SI models may be applied in a geographic information systems (GIS) environment to develop an integrated methodological approach, especially for heterogeneous media, that considers geological, hydrological and geochemical data to improve the reliability of risk estimation. The major advantage of GIS-based groundwater vulnerability mapping is the use of data layers and the consideration of spatial variability of the parameters used for risk estimation. The resulting vulnerability maps can be easily used by local authorities, decision makers and policy makers for designing groundwater protection and remediation strategies [4].

Hence, the aim of this study is to estimate groundwater vulnerability to contamination in the island of Aegina, Greece, using three well-established models (Generic DRASTIC, Pesticide DRASTIC and SI), which are suitable for shallow coastal aquifer systems and agricultural areas. Sensitivity analysis and validation of models were also carried out to evaluate, compare and validate the obtained results in terms of subjectivity and variation of parameters.

2. Study area

2.1. Location, topography and climate

Aegina is located approximately 16.5 miles south of Athens and is the second largest island in the Saronic Gulf (after Salamis) with a total surface area of 87 km^2 and a coastline of 57 km (Fig. 1). The municipality of Aegina has 13,046 permanent inhabitants (based on 2011 census data), and this number increases to 60,000 during summer. Tourism and agriculture are the main activities in the island, followed by fishing and commerce [12].

The topography of the study area is typical to most islands of the Aegean Sea and the Saronic Gulf, and includes coastal plains and mountainous areas with hilly intermediate formations. The vast majority of the coastal plains (up to 30 m.a.s.l) are located in the northwest (Aegina town and Kipseli) and north (Souvala and Vagia) parts, which are characterized by higher population density, and long-lived trees (mainly pistachio orchards and olive groves) are cultivated. On the other hand, the mountainous areas, which are located in the central and south regions, present a discordant relief with blunt summits and form escarpments to the coast, with 30–60 m height and cone landforms, which do not allow a consistent growth of vegetation.

The island of Aegina is characterized by semi-arid Mediterranean climate with a mean annual temperature of 19°C [13]. The average annual precipitation is around 295 mm; approximately 80% of the annual precipitation falls

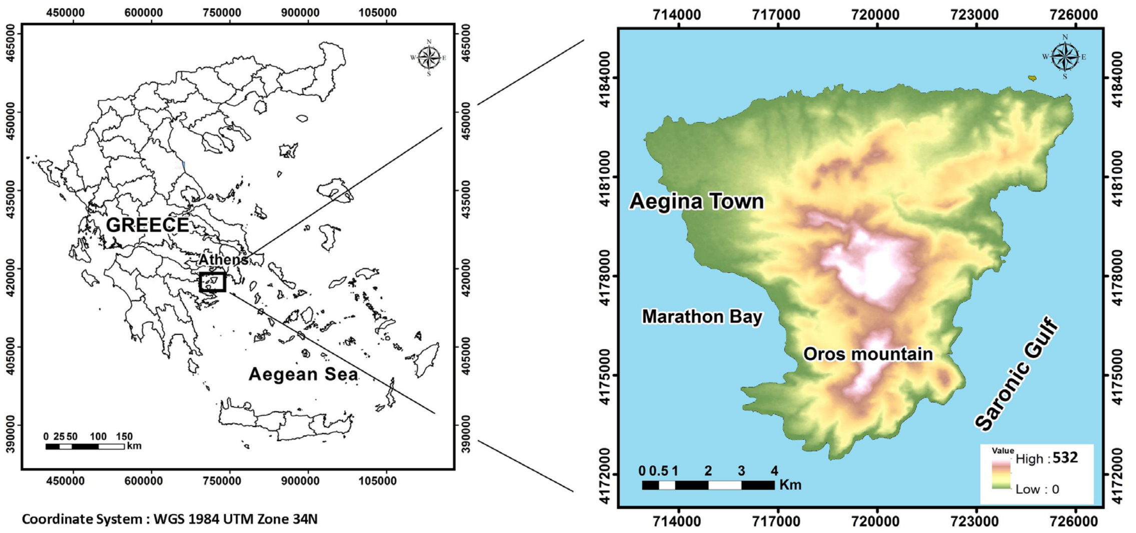

Fig. 1. Location and altitude map of the study area.

during the wet season between November and April, while summers are usually dry.

2.2. Geology and hydrogeology

Aegina is a Plio-Pleistocene volcanic island with two geomorphological settings (Fig. 2) [14–16]: (i) a permeable region (34% of the total area of the island) located in the north and covered by Neogene lacustrine along with shallow marine sediments, which are partly covered by beds of "Poros" limestone and Pleistocene marls, and (ii) a less permeable region (66% of the island) covered by large volcanoclastic dacitic flows, plugs and necks, as well as by minor andesitic lava flows that have formed at or near sea level. The geological basement comprises mainly Permian to Upper Cretaceous limestones covered by flysch and ophiolitic thrust sheets. The current geological state of the island is the result of two series of eruptions occurred during Pliocene and Plio-Pleistocene ages, followed by a recent uplift and erosion.

From a hydrogeological point of view, the mountains of Aegina (mainly the Oros Mountain) form four major water basins (catchment areas of Skoteini, Viros, Mesagros and Glyfada). In the rest of the island, there are no significant water catchments or basins. The main drainage network exhibits radial arrangement that starts from the central mountainous part and involves several seasonal steams flowing into the sea. A secondary network has been developed in Neogene marly rocks close to the stream of Glyfada and extends into porous formations. In addition, several streams exist in the central northwestern part of the island but they do not reach the shoreline since they flow through volcanic breccia rocks with high permeability [14,17]. The dominant aquifer systems are mainly located in alluvial deposits and limestones in the north part of the island. Aquifer permeability increases towards the coast due to the major karstic development, while the groundwater table usually fluctuates between 10 and 60 m.

2.3. Land use and environmental issues

The north part of the study area is intensively cultivated, and the major land uses include family orchards with pistachio trees, which are scattered in the urban areas (Fig. 3). Approximately 32% of the cultivated land is irrigated while the rest is dry or rain-fed [18]. The main cultivations in the irrigated land are pistachios 63%, olive trees 20%, almond trees 7%, citrus trees 4%, vineyards 2% and others 4%. Most of them require irrigation to maintain constant yield although they are well adapted to the ecological conditions of the Mediterranean region. It is mentioned that the annual requirements of pistachio orchards in terms of nitrogen (N) are extremely high, ranging between 150 and 230 kg ha^{-1}, while the annual water needs may be as high as 7,000 m^3 ha^{-1} [19]. The average area of a typical farmholding in the study area is approximately 0.4 ha, while the dominant soils are shallow Cambisols, Fluvisols and Leptosols according to the soil taxonomy of FAO [20].

Geomorphology, drainage networks and land uses in Aegina present certain geographical, social and economic features, which render them disadvantageous or under risk. During the last decades, the use of groundwater resources has become particularly intensive in coastal areas, which are characterized by intense urbanization, touristic development and irrigated land expansion. Groundwater and soil in the study area may be contaminated due to the intrusion of seawater as a result of overexploitation of coastal aquifers, the use of fertilizers/pesticides in agriculture [21,22] and the uncontrolled disposal of wastewater/solid waste [19].

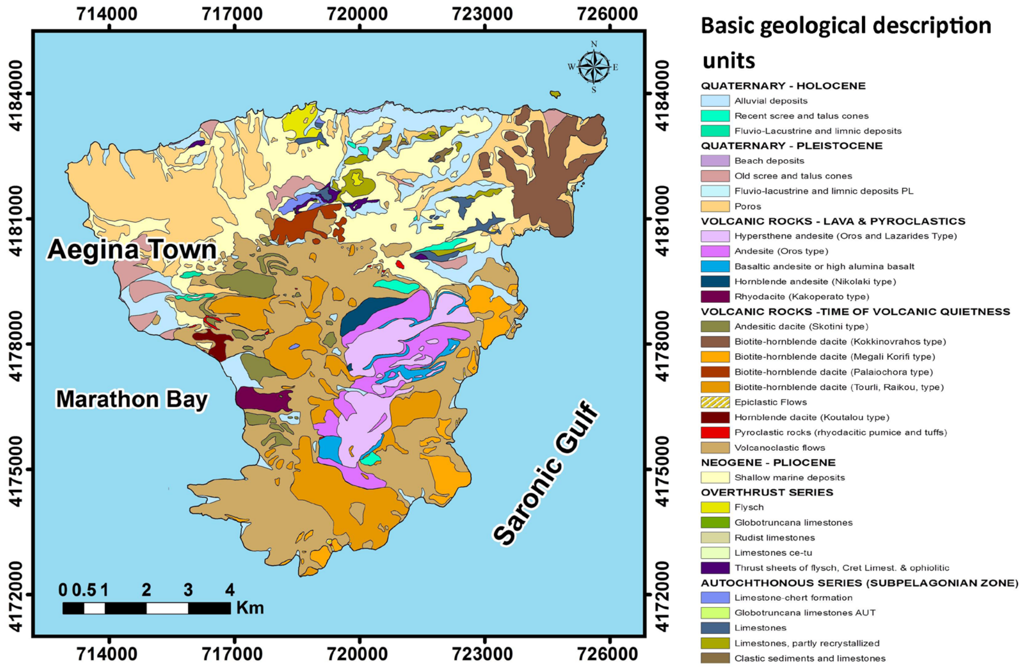

Fig. 2. Geological settings of the study area.

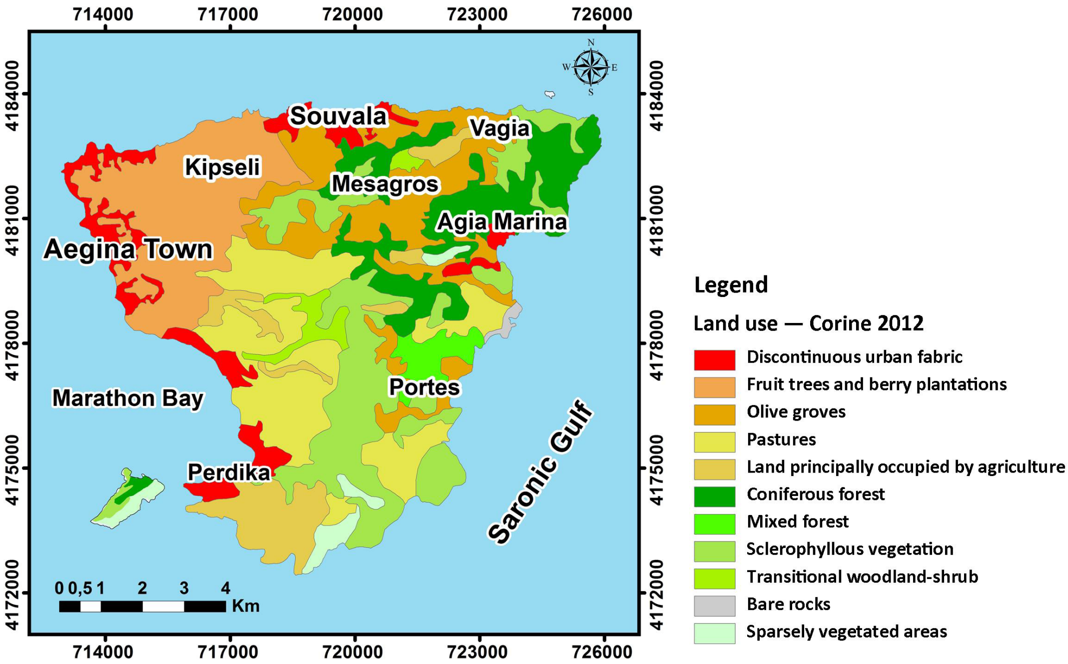

Fig. 3. Land use map of the island of Aegina according to the Corine Land Cover [18].

In some cases, both municipal solid and other waste (mainly from agricultural activities) are disposed uncontrolled in landfills.

3. Materials and methods

3.1. GIS-based models for groundwater vulnerability assessment

Three different GIS-based models (Generic DRASTIC, Pesticide DRASTIC and SI) were used to evaluate the overall groundwater vulnerability in the study area and are described below in detail.

3.1.1. Generic and Pesticide DRASTIC models

The DRASTIC model uses the most popular subjective rating method to evaluate groundwater vulnerability within various hydrogeological settings [4,23]. This approach adopts a numerical index deriving from rated and weighted values, which are assigned to seven different spatial parameters, namely depth to water (*D*), net recharge (*R*), aquifer media (*A*), soil media (*S*), topography (*T*), impact of vadose zone (*I*) and hydraulic conductivity (*C*). The DRASTIC index (DI) is quantified by a linear combination of rated and weighted values of the seven parameters according to Eq. (1):

$$\text{DRASTIC index (DI)} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W \quad (1)$$

where DRASTIC index (DI) represents vulnerability; acronyms *D*, *R*, *A*, *S*, *T*, *I* and *C* refer to the seven parameters of the DRASTIC model and subscripts W and R represent their corresponding weighted and rated values, respectively.

Table 1
Parameters and weights assigned in the two DRASTIC models

Parameter	Acronym	DRASTIC models	
		Generic	Pesticide
Depth to water	*D*	5	5
Net recharge	*R*	4	4
Aquifer media	*A*	3	4
Soil media	*S*	2	5
Topography	*T*	1	3
Impact of vadose zone	*I*	5	4
Hydraulic conductivity	*C*	3	2

DRASTIC provides two different weighting modes: Generic DRASTIC for normal conditions prevailing in areas where urban activities are carried out and Pesticide DRASTIC for areas with intense agricultural activity. Once the DI is evaluated, it is possible to identify areas that are more vulnerable to groundwater contamination. Depending on the DRASTIC model, several classes of each parameter are gauged and assigned scores from 1 to 10, while the seven parameters are assigned weighted values ranging from 1 to 5 based on their significance (Table 1). Higher values of the DI imply greater vulnerability to groundwater contamination.

Despite its unique characteristics and wide applicability, DRASTIC is based upon four key assumptions: (i) the contaminant is present on the ground surface; (ii) the contaminant is flushed into groundwater by precipitation; (iii) the contaminant has the mobility of water and (iv) the area under evaluation is 0.4 km^2 or larger [5,23].

3.1.2. Susceptibility index model

SI model is an adaptation of the well-established DRASTIC model for evaluating the specific vertical vulnerability to groundwater contamination [10,24]. This model involves four of the original DRASTIC parameters, i.e., depth to water (*D*), net recharge (*R*), aquifer media (*A*) and topography (*T*), and also includes the additional parameter of land use (*LU*), which takes into account the impact of agricultural activities (such as fertilizer and pesticide application) on groundwater quality. Previous studies have shown that soil type can largely influence the attenuation potential of certain contaminants, while its effect on groundwater vulnerability can be indirectly estimated by considering land uses [24]. This is because the quality characteristics of available natural soils often change during land cultivation. The quantified SI is expressed by Eq. (2):

$$\text{Susceptibility index (SI)} = D_R D_W + R_R R_W + A_R A_W + T_R T_W + LU_R LU_W \tag{2}$$

where *D*, *R*, *A*, *T* and *LU* are the acronyms of the five parameters assessed, and the subscripts W and R are their corresponding values.

Table 2 displays the assigned values for each parameter based on the SI model. The principal classes of land use are based on Corine Land Cover (Legend III), and their assigned values range between 0 and 100 according to the SI model (Table 3).

Table 2
Parameters and weighting values in SI model

Parameter	Acronym	Weight
Depth to water	*D*	0.186
Net recharge	*R*	0.212
Aquifer media	*A*	0.259
Topography	*T*	0.121
Land use	*LU*	0.222

Table 3
Land use occupation classes and their assigned SI ratings

Land use	Rating
Industrial discharge, landfill, mines	100
Irrigated perimeters, paddy fields, irrigated and non-irrigated annual culture	90
Quarries, shipyards	80
Artificial covered zones, green zones, continuous urban zones	75
Permanent cultures (vines, orchards, olive trees, etc.)	70
Discontinuous urban zones	70
Pastures and agro-forest zones	50
Aquatic milieu (swamps, saline, etc.)	50
Forest and semi-natural zones	0

3.2. Data collection techniques and methodology

Several data collection techniques and procedures were used to obtain the accuracy required for the specific requirements of each GIS-based model used (Generic DRASTIC, Pesticide DRASTIC and SI). These included primary data obtained from in situ measurements in the frame of the ongoing AgroStrat project (http://www.agrostrat.gr/) [19,25], in order to assess water and soil quality in the study area as well as secondary data concerning geospatial (mainly land use and topography) and hydrogeological features, which were obtained from official websites of national agencies and local authorities.

The flowchart that represents the various processing steps of the methodological approach followed in this study is shown in Fig. 4. The proposed methodology explores the capabilities provided by GIS to detect spatial patterns of data by combining aquifer vulnerability and actual groundwater pollution sources.

3.3. Sensitivity analysis

The assessment of groundwater vulnerability requires additional statistical support to reduce subjectivity, increase reliability and therefore minimize doubts pertinent to the accuracy of the GIS-based models used [26]. To this extent, sensitivity analysis defines uncertainty, estimates variability and relative changes of the obtained results using different sets of input parameters, and thus fully identifies the most critical parameters that affect the reliability of groundwater vulnerability. This statistical tool is essential both for scientists to construct groundwater vulnerability maps and for policy makers and decision makers to evaluate current land use practices and future land management planning [27].

In the present study, single-parameter sensitivity analysis was carried out to assess the influence of input parameters on

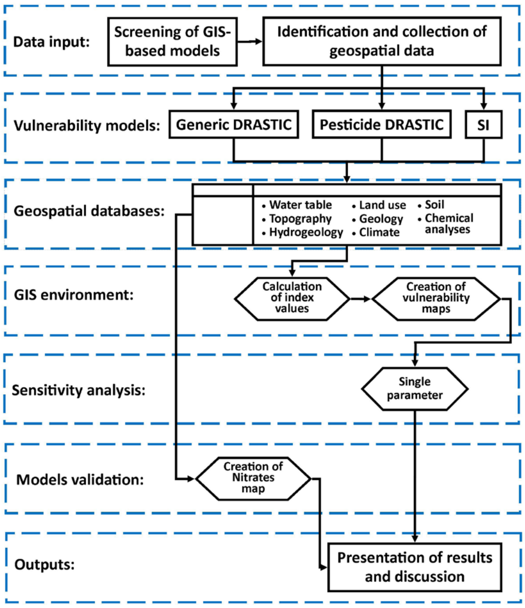

Fig. 4. Schematic flowchart of the methodology adopted in this study.

the calculated groundwater vulnerability for the models used [28]. Therefore, the real or effective weight of each parameter was compared with the assigned or theoretical weight in each polygon of the resulting groundwater vulnerability map. The effective weight of each *i*th sub-area was obtained using the Eq. (3):

$$W_{xi} = \left(\frac{X_{ri}X_{wi}}{V_i}\right)\times 100 \tag{3}$$

where W_{xi} refers to the effective weight of each parameter; X_{ri} and X_{wi} represent the rating and the weight assigned to a parameter (x) in the *i*th sub-area, respectively, while V_i is the overall calculated vulnerability index (unperturbed).

4. Results and discussion

4.1. GIS-based models for groundwater vulnerability assessment

Seven maps for each one of the original DRASTIC parameters were produced using ArcGIS 10.1. An additional map of land use was produced for the estimation of the groundwater vulnerability index according to SI model. Each map was classified and assigned rated and weighted values according to DRASTIC (Generic and Pesticide) and SI models. The final features obtained (raw input or classified) in the spatial analysis are presented in the following raster maps and discussed in detail.

4.1.1. Depth to water (D)

Depth to water refers to the distance of the ground surface from the water table. Therefore, deeper water table levels imply lesser chance for contamination of the aquifer. Water level measurements obtained from 62 observation piezometer wells and boreholes [18] scattered in the study area were spatially interpolated via kriging [29] to create the distribution map of *D* (Fig. 5(a)). Apart from these primary source data covering the period 2013–2014, water well records (44 in total) covering the period (2005–2008) were also taken into account [30].

Depth to water table in the study area varies between 9.6 and 62.6 m, and gradually decreases from the central part of the island to the coastal boundaries in all directions. More specifically, *D* in most parts (40.4% of the study area) covered by volcanic rocks such as volcanoclastic flows and dacites ranges between 62.6 and 30.4 m. However, the mean depth of the regional water table is about 15–20 m, while the lowest water levels (as low as 9.6 m) were observed in the northwestern coastal plain of Aegina town, which is dominated by shallow and beach deposits. A total of four classes were extracted concerning *D*, and rated values ranging from 1 to 5 were assigned with regard to DRASTIC classification.

4.1.2. Net recharge (R)

The net groundwater recharge is an important parameter of groundwater vulnerability and accounts for the amount of precipitation water that percolates and transports contaminants into the aquifer. However, the estimation of this parameter presents a real challenge in most hydrogeological settings since the use of a single reliable method, that is characterized by limited uncertainty and errors, is a difficult task [31]. In the present study, R was estimated using the chloride mass balance equation [32]:

$$R = P\frac{\mathrm{Cl}_p}{\mathrm{Cl}_g} \tag{4}$$

where R is the net recharge; P is the mean annual precipitation (mm y^{-1}); Cl_p is the Cl concentration in precipitation (mg L^{-1}) and Cl_g is the Cl concentration in groundwater (mg L^{-1}). The main assumptions of this approach are: (i) Cl is inert in natural environments and (ii) all Cl derives solely from evapotranspiration [33]. Integrated annual precipitation data during the period 2013–2015 were obtained from 2 meteorological stations of the island, operated by the National Observatory of Athens and the AgroStrat project team [13,34]. Chloride concentration levels in groundwater were obtained from 62 sampling points during the period 2013–2014 [18], while average chloride concentration in precipitation was taken from literature [35].

The map of *R* (Fig. 5(b)) was created by reclassifying data into intervals and assigning rated values as indicated by the DRASTIC model. The less rechargeable zone (0–50.8 mm y^{-1}) is located in the northeastern part (15%) of the study area (between Souvala and Agia Marina), where fluvial and marine deposits, soil erosion and less precipitation are

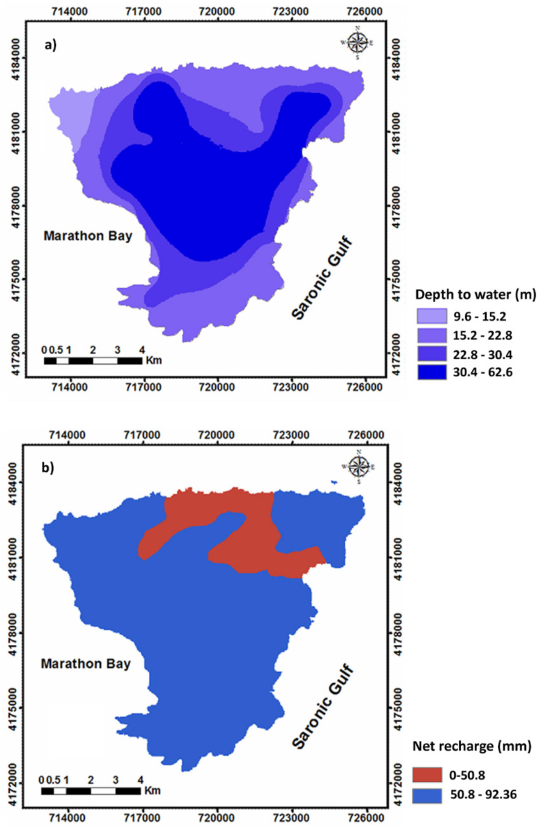

Fig. 5. Spatial distribution of (a) *D* and (b) *R* inputs in the study area.

observed, while the remaining part of the study area (85%) has the highest R values (50.8–92.6 mm y^{-1}).

4.1.3. Aquifer media (A)

The aquifer media parameter depends on the type of the formation (consolidated or unconsolidated), which serves as reservoir for water. It mainly distinguishes aquifer types according to their geological framework (limestone, sandstone, sand, gravel, etc.), boundaries and thickness. The A map in the study area was prepared using data from the geological map of Aegina (1:25,000) [36], while the available hydrogeological and lithological profiles were synthesized by the Greek Institute of Geology and Mineral Exploration (IGME) [37]. The map was then digitized and classified on the basis of the assigned index values of DRASTIC model. Classified mapping results showed that the larger part of the study area (72%) is covered by shales and dolomites, and receives a moderate rating of 6, followed by highly permeable limestones (20.5%) located in the northwestern region (Fig. 6) which are rated with 8. The highest rating of 10, applied to 7.5% of the total area, is assigned to the north aquifer system, which comprises newly formed and shallow marine deposits.

4.1.4. Soil media (S)

The soil media is the uppermost part of the vadose zone (approximately 1–2 m thick) and indicates the recharge rate that can infiltrate soil and cause groundwater contamination. For the classification of dominant soil textures in the study area, the point shapefile containing soil textural data was converted to a polygon shapefile through Thiessen polygon tessellation. Four soil textural classes are extracted based on data provided by AgroStrat project [25], and a rating value varying between 4 and 9 was assigned to each class. Depending on the parent material, soil textural classes include silty loam (1.3%), sandy loam (58.4%), peat (1.7%) and sand (38.6%) (Fig. 7(a)). More than half of the soils in the island are very shallow in depth, i.e., from 0 to 15 or 0 to 30 cm. In general, north and northwestern parts of the study area, which are fully covered by highly permeable deposits and are shallow in depth, i.e., 0–30 cm, indicate higher attenuation of soil contamination compared with other parts that are composed of silty/clay and sandy loam soils and are characterized by lower attenuation.

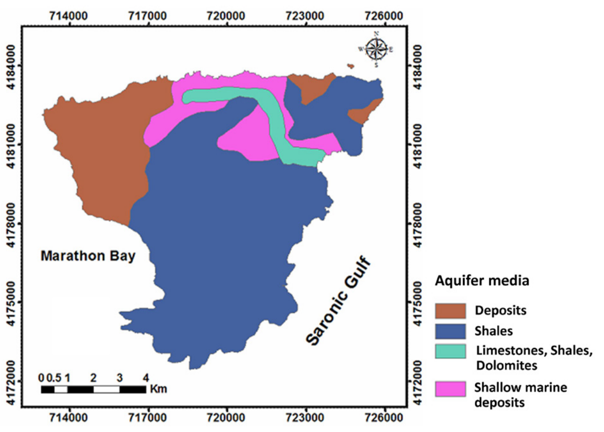

Fig. 6. Spatial distribution of A input in the study area.

4.1.5. Topography (T)

For the creation of the topography map, a Digital Elevation Model (DEM) using contour interpolation of 30 m was prepared in a raster format. Terrain slope (Slope$_{pct}$) was then calculated according to the following exponential hypotenuse (HYP) (Eq. 5):

$$\text{Slope}_{\text{pct}} = \left(\frac{\text{HYP}(DX,DY)}{\text{PIXSIZE}(DX)}\right) \times 100 \quad (5)$$

where DX is the horizontal gradient map, and DY the vertical gradient map.

The slope map of the study area, shown in Fig. 7(b), is highly complex, and the slope varies within a wide range, from 0% to 38%. More precisely, parts with mixed flat (<2%) and gentle slope (2%–6%) located on the northwestern side of the island, around Aegina town and Kipseli, and in Perdica at southwest, were identified covering 13.9% and 16.1% of the total area under study, respectively. Both areas, given their inherent ability to intercept runoff, were assigned the highest DRASTIC scores of 9 and 10. Higher slopes (6%–12%) were depicted in parts of the island where hilly terrains

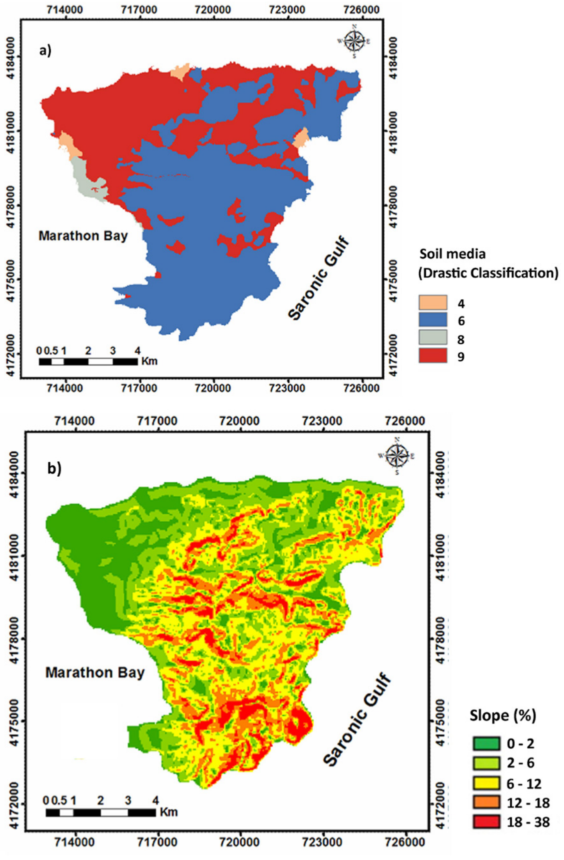

Fig. 7. Spatial distribution of (a) classified S output and (b) T input in the study area.

predominate (30.1%) and assigned the medium score of 5. It is important to note that considerable part of the study area (~19%), located mainly in the central and south regions (close to the shore), is characterized by very steep slopes (up to 38%). This rugged terrain is composed of rock formations and chasmophytic vegetation.

4.1.6. Impact of vadose zone (I)

The impact of vadose zone represents the texture of the unsaturated zone above the water table, which controls fate, attenuation and the time the contaminants need to reach groundwater. In this study, a vadose zone map was produced based on available geological and lithological layers obtained from IGME [30,37]. It was found that 23.8% of the total area, located mainly in the central and southern regions of Aegina, has vadose zone consisting of silt/clay formations and thus was assigned a rating of 3 (Fig. 8(a)). Limestone formations occupy most central and northeastern parts (34.3%), while sand and gravel settings (11.7%) dominated areas around the towns of Aegina, Agia Marina, Vagia and Souvala, as shown in Fig. 8(a). These two ranges of hydraulic conductivity were assigned scores of 6 and 8, respectively. In the coastal plain of Aegina town (30.2%), the vadose zone consisting of basalts was assigned the highest value of 9.

4.1.7. Hydraulic conductivity (C)

The map of hydraulic conductivity was obtained through spatial interpolation of bedrock geology datasets obtained from IGME and other previous studies (Fig. 8(b)) [14,16,30,36,37]. In general, the study area is characterized by high hydraulic conductivity (0.05–0.08 cm s^{-1}) in the northwestern part (20.5%), and thus the high score of 8 was assigned. Based on mapping data, it is deduced that moderate permeability values (0.03–0.05 cm s^{-1}) dominate the rest of Aegina (75%), except for a narrow strip zone (4.5%) identified in north/northeast where less permeable hydrogeological settings exist and permeability ranges between 0.01 and 0.03 cm s^{-1}.

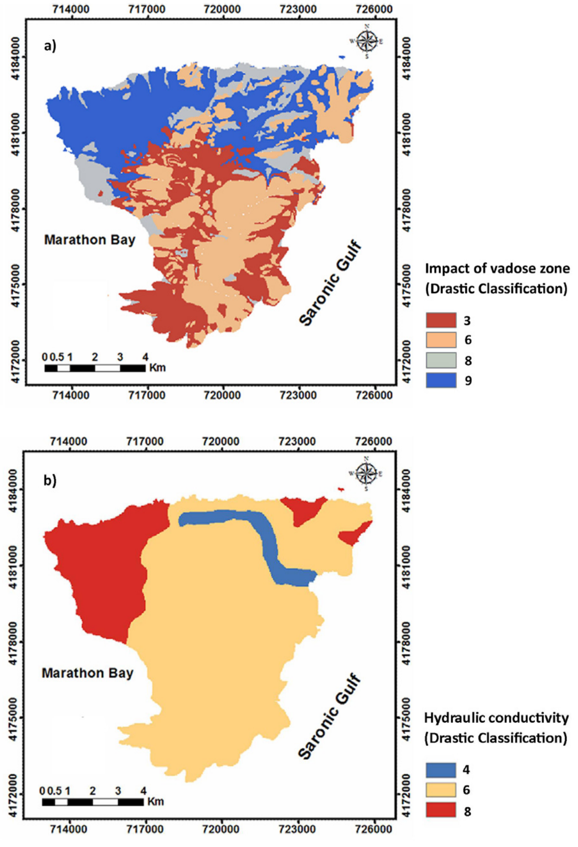

Fig. 8. Spatial distribution of classified (a) *I* and (b) *C* outputs in the study area.

4.1.8. Land use (LU)

Land use is considered an important parameter since it affects hydrological conditions. The spatial distribution of land use in the study area has been mostly mapped using remote sensing data of the Corine Land Cover (Fig. 9) [18]. However, the initial Corine input data were slightly modified after comparing them with recent colour orthophotos (1:1000) [38]. According to SI classification, the lowest score of 0, representing no effect on vulnerability, was assigned to about 16% of the total area, which is covered by forest land. An equal part of the study area (18%), in the central region of the island, was assigned a score of 50 due to pasture-related agricultural activities. The highest score of 70 was assigned to the remaining part of the study area (66%), indicating that when the land use parameter is considered urban and irrigated agricultural areas (mainly pistachio cultivations) have the highest impact on vulnerability.

4.2. Generic DRASTIC, Pesticide DRASTIC and SI groundwater vulnerability maps

Generic DRASTIC, Pesticide DRASTIC and SI groundwater vulnerability maps were created by summing up the assigned parameters (depth to water [*D*], net recharge [*R*], aquifer media [*A*], soil media [*S*], slope [*T*], impact of vadose zone [*I*], hydraulic conductivity [*C*] and land use [*LU*]) on a raster cell-by-cell basis according to Eqs. (1)–(3). The resulting groundwater vulnerability maps, based on the produced indices, were then reclassified into five equal categories of contamination risk in order to evaluate the spatial distribution

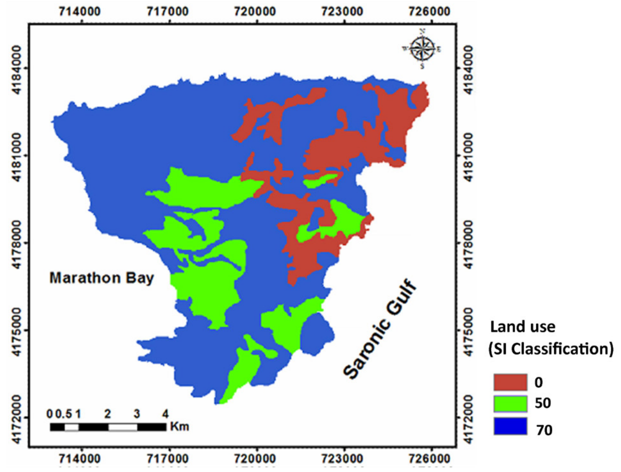

Fig. 9. Spatial distribution of classified *LU* in the study area.

patterns of groundwater vulnerability over the area under study. Overall, high values for groundwater vulnerability indices indicate areas with high contamination risk and high spatial variance of the geospatial input parameters that need to be monitored more intensely. All groundwater vulnerability maps are shown in Fig. 10. Legend values in these figures indicate risk categories, namely no, low, medium, high and very high.

Groundwater vulnerability index values obtained from the Generic DRASTIC model varied from 67 to 154, whereas index values obtained from the Pesticide DRASTIC varied from 88 to 194 (Table 4). On the other hand, the respective values obtained from the SI model were much lower, ranging from 21 to 65, solely due to the use of smaller values and number of parameters.

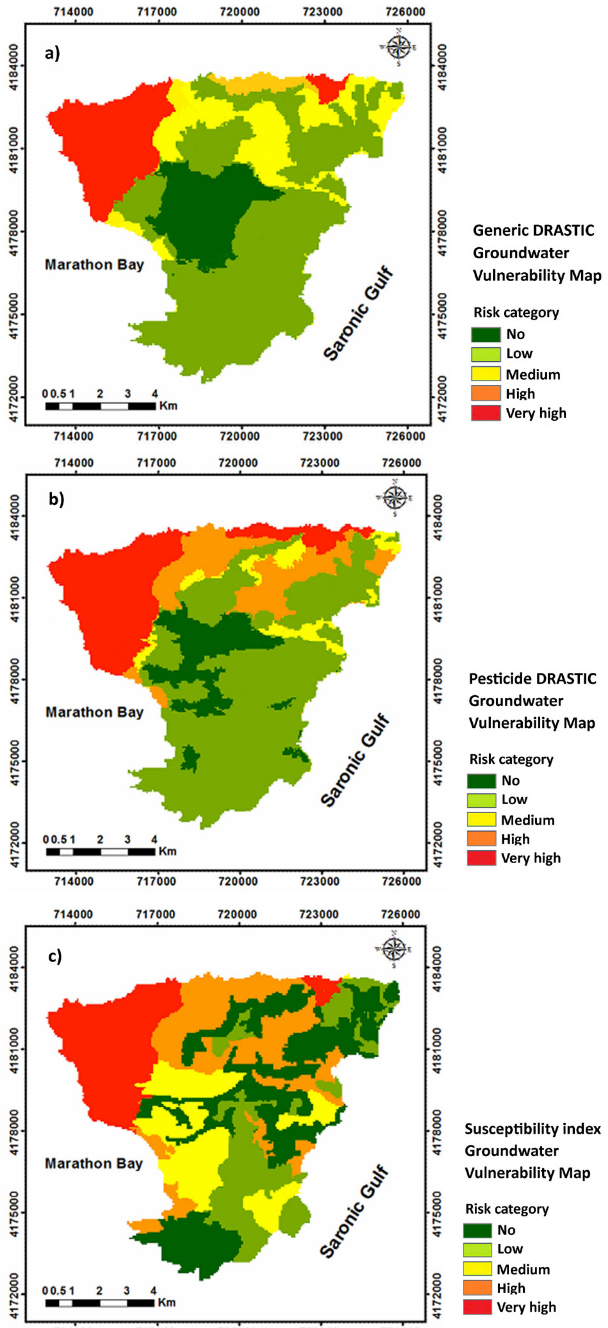

Fig. 10. (a) Generic DRASTIC, (b) Pesticide DRASTIC and (c) SI groundwater vulnerability map in the study area.

Overall, similarities were found across the obtained mapping results of the three GIS-based models used, including areas that are characterized by "high" to "very high" risk mainly located in the northwest part of the island; these areas are mainly covered by permeable "Poros" limestones and alluvial deposits. Categorized areas with very high risk were almost identical for both the Generic DRASTIC and SI models, and occupied 18.0% and 18.3% of the island, respectively. On the contrary, larger areas (22.5%) characterized by "very high" risk for groundwater contamination were identified after the application of the Pesticide DRASTIC model. This indicates that apart from the coastal plains of Aegina town and Vagia, which identified after the application of the two other GIS-based models, a highly vulnerable area was also identified along the coastline of Souvala. In this area intensive agricultural activities, mainly associated with pistachio orchards, requiring high application rates (230/70/200 kg h^{-1}) of N/P/K fertilizers are carried out; these rates are two or even three times higher than those used in other cultivations such as olive trees [39] and citrus trees [40], and thus continuous monitoring is required. These monitoring activities should involve sampling of composite samples from existing wells, boreholes and soils above aquifer media, new drillings and sampling of wells in hotspots, adoption of groundwater monitoring programmes and protocols, minimization of groundwater irrigation activities, and implementation of pesticide management/control practices to reduce risk for groundwater contamination.

Based on the results of the Generic DRASTIC model, which are shown in Fig. 10(a), exactly half (50.0%) of Aegina island is characterized by "low risk"; this is mainly due to its steep topographic gradient (>6%), medium uniform distribution of hydraulic conductivity (0.03–0.05 cm s^{-1}) and high impact of soil media (DRASTIC weight of 6). Similarly, the groundwater vulnerability map of the Pesticide DRASTIC model was dominated by "low risk" areas (48.3%), whereas significantly lower land occupation (17.4%) with similar risk was identified by the SI model when the land use parameter was considered.

Similar values of medium risk for groundwater contamination were observed after the application of SI and Pesticide

Table 4
Risk categories for the Aegina Island based on the Generic DRASTIC, Pesticide DRASTIC and SI indices

Frequency of index	DRASTIC indices range		SI	Risk category
	Generic	Agricultural		
0–20	67–85	88–109	21–30	No
20–40	85–102	109–130	30–39	Low
40–60	102–119	130–152	39–47	Medium
60–80	119–136	152–173	47–56	High
80–100	136–154	173–194	56–65	Very high

DRASTIC models, mainly in the mid-part of Aegina and the hilly areas of Mesagros occupying 16.3% and 16.2% of the study area, respectively. The moderate groundwater vulnerability indices in these areas were probably due to the synergistic effect of several factors, mainly including the alluvial aquifer media corresponding to the shallow marine deposits and the low net recharge values (0–50.8 mm) for the Pesticide DRASTIC model. Also, these factors reflect the effect of land use and, to a lesser degree, the quite steeper slopes (6%–12%) considered in the SI model.

Moreover, "no" risk areas were restricted to only a small part of the study area (13.8% and 11.1% for the Generic and Pesticide DRASTIC models, respectively) located southeast of Aegina town and representing primarily areas of deep water table, on average 50 m, and less impactful vadose zone (score 3). The application of the SI model indicates that a larger part of the study area (26.0%), scattered over the entire island, is characterized by very low vulnerability; such low vulnerability is also calculated in an area located north, where shallow aquifer systems are present.

Based on the above results, it is clearly demonstrated that the overall groundwater vulnerability in the study area increases from south to north and corresponds well with the increasing clay content in soil and the decreasing slope of topography and impact of vadose zone along the same direction.

4.3. Single parameter sensitivity analysis

The single parameter sensitivity analysis was carried out for the seven input parameters of the Generic DRASTIC (Table 5) and Pesticide DRASTIC models (Table 6) as well as for the five input parameters of the SI model (Table 7).

Results of single parameter analysis clearly indicate that the impact of vadose zone (*I*) parameter, with a mean effective weight of 24.2% against the theoretical weight of 21.7%, dominated the Generic DRASTIC vulnerability index. However, among all parameters of the Generic DRASTIC model, the net recharge (*R*) showed the greatest difference between theoretical and effective weights, i.e., a negative 55.2% change in comparison with its theoretical weight (17.4%) was observed, thus indicating that this parameter has the lowest impact in the estimation of the Generic DRASTIC groundwater vulnerability index. On the contrary, the aquifer media (*A*) parameter presented the highest positive change (49.4%) of its effective weight (19.5%) when compared with its theoretical weight (13.0%).

Table 5
Statistical summary of the single parameter sensitivity analysis for the Generic DRASTIC model

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Minimum	Maximum	Mean	Standard deviation (SD)
D	5	21.7	7.5	16.2	12.7	4.5
R	4	17.4	6.0	9.5	7.8	2.8
A	3	13.0	18.5	26.9	19.5	4.9
S	2	8.7	11.7	12.6	11.9	3.0
T	1	4.4	1.5	6.5	5.7	3.0
I	5	21.7	22.4	25.5	24.2	9.4
C	3	13.0	9.0	16.6	15.6	2.9

Table 6
Statistical summary of the single parameter sensitivity analysis for the Pesticide DRASTIC model

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Minimum	Maximum	Mean	Standard deviation (SD)
D	5	18.5	5.7	21.9	12.9	4.5
R	4	14.8	4.6	14.1	10.2	2.8
A	4	14.8	10.4	21.3	16.6	6.5
S	5	18.5	20.6	23.2	22.7	7.5
T	3	11.1	3.4	18.4	15.5	8.9
I	4	14.8	13.6	21.6	18.6	9.1
C	2	7.4	4.6	9.9	8.3	1.9

Table 7
Statistical summary of the single parameter sensitivity analysis for the SI model

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Minimum	Maximum	Mean	Standard deviation (SD)
D	5	21.7	17.5	23.2	20.7	4.5
R	4	17.4	16.0	19.5	17.1	2.8
A	3	13.0	11.5	19.9	15.5	4.9
T	2	8.7	7.7	10.6	9.1	3.0
LU	3	12.0	9.0	16.6	13.6	2.9

The calculated effective weight for the impact of *C* (15.6%) exceeded by 13.0% of its theoretical weight assigned by the Generic DRASTIC model. The weighted parameters of S and T displayed higher effective values (11.9% and 5.7%, respectively) than their theoretical ones (8.7% and 4.4%, respectively), thus reflecting their importance for the calculation of groundwater vulnerability index using the Generic DRASTIC model.

Table 6 reveals that the *T* was the most effective parameter during vulnerability assessment as its effective weight (15.5%) exceeded by 39.2% the theoretical weight imposed by the Pesticide DRASTIC model (11.1%). This statistical result shows the very high importance of *T* in the resulting groundwater vulnerability map of Pesticide DRASTIC model, thus suggesting the need for more precise data on this parameter in order to address site-specific differences.

On the contrary, R showed the lowest impact in the estimation of Pesticide DRASTIC groundwater vulnerability index, since it exhibited a negative 31.2% change in comparison with its theoretical weight (14.8%). Regarding *S* (18.6%) and *I* (14.9%), their effective weights increased moderately by 22.7% and 25.7%, respectively, while *A* and *C* were the least influential among all positively correlated DRASTIC parameters considered, due to their similar effective values compared with the theoretical ones.

Finally, single parameter sensitivity results clearly indicate that *A* is the most effective parameter during groundwater vulnerability mapping with the use of the SI model and its mean effective weight of 15.5% exceeded by 18.7% of its theoretical weight of 13.0%. Mean effective weights of *T* and *LU*, 9.1% and 13.6% respectively, were almost equal to their respective theoretical weights. On the other hand, the parameters *D* and *R* showed negative change by 4.9% and 1.7%, respectively, when compared with their theoretical weights (21.7% and 17.4%, respectively), thus indicating that these parameters were the less impactful in the estimation of the SI groundwater vulnerability index.

4.4. Validation of the Generic DRASTIC, Pesticide DRASTIC and SI models

The validation of the results derived by the DRASTIC and SI models was performed by considering the spatial variation of available nitrate concentration values in the aquifer systems of the study area. Nitrate concentration was selected as the most representative indicator to verify mapping results based on the fact that groundwater is highly impacted by NO_3–N. As already mentioned earlier, this is largely due to leaching and runoff of nitrates to groundwater, as a result of the high rates (>200 kg ha^{-1}) of nitrogenous fertilizers that are applied in pistachio orchards in Aegina along with the rates of irrigation water, which can be as high as 7,000 m^3 ha^{-1} [18]. In addition, since both Pesticide DRASTIC and SI models assume that contaminants are mobile and water-soluble, nitrates fully satisfy these assumptions.

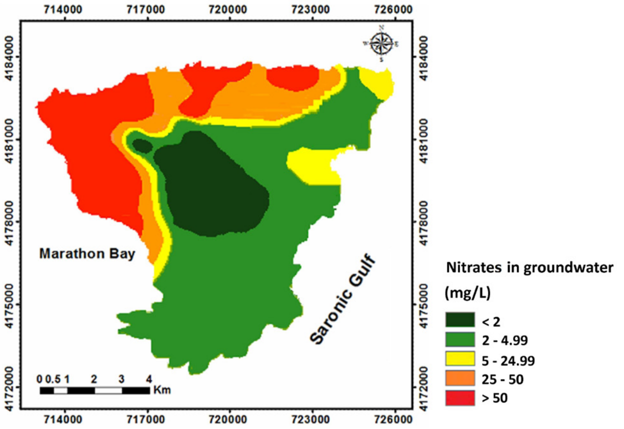

Fig. 11. Actual concentration of nitrates in the groundwater of the study area.

The spatial distribution of nitrates in groundwater was obtained using spatial interpolation/kriging techniques (Fig. 5). As in the case of the depth to water (*D*) parameter, recent data on nitrates concentration were provided from 62 sampling locations by AgroStrat project (period 2013–2014) [18] and from 44 water wells from IGME (period 2005–2008) [29]; thus, actual values from 106 sampling locations covering the entire study area were used in total. Nitrate concentrations were divided into five classes based on its permissible concentration of 50 mg L^{-1} (Nitrates Directive 91/676/EC and Drinking Water Directive 98/83/EC) [41,42], as follows: level 1: <2 mg L^{-1}; level 2: 2–4.99 mg L^{-1}; level 3: 5–24.99 mg L^{-1}; level 4: 25–50 mg L^{-1} and level 5: >50 mg L^{-1}.

Fig. 11 shows the actual concentration of nitrates in Aegina groundwater. As it is easily deduced, areas with “very high” vulnerability, covering 22.2% of the island, are characterized by elevated nitrate concentrations (>50 mg L^{-1}), while nitrate concentrations classified in levels 1 and 2 (below 5 mg L^{-1}) report in "no" and "low" risk areas, i.e., 63.6% of the total area. The obtained Pearson's correlation coefficients between the Generic DRASTIC, Pesticide DRASTIC and SI models for the actual nitrate concentrations were 0.679, 0.748 and 0.563, respectively, thus indicating that both DRASTIC models are characterized by fairly good (Generic) to almost very good (Pesticide) accuracy. The nitrate-vulnerability validation results obtained in this study are in very good agreement with results obtained from earlier studies carried out in other agricultural areas [43–45].

High levels of nitrates in groundwater are due to extensive and intensive agricultural activities carried out in the coastal plain between the towns of Aegina and Kipseli, which cause nitrate pollution as a result of the high hydraulic conductivity of the bedrock ("Poros" limestones) and the flat topography of the area.

Overall, the results of this study indicate that the Pesticide DRASTIC is the most suitable model to assess groundwater vulnerability for coastal aquifers in regions where combined urban and agricultural activities are carried out; these areas are therefore subject to contamination due to the use of agrochemicals. Land use changes considered in the estimation of the SI seem to be less important compared with the seven hydrological parameters used in both DRASTIC models. However, in order to further increase accuracy of groundwater vulnerability mapping, additional monitoring data pertinent to soil and groundwater need to be obtained and analyzed.

5. Conclusions

In this study, three well-known GIS-based models, namely the Generic DRASTIC, the Pesticide DRASTIC and the SI, were applied for the assessment of groundwater vulnerability in the island of Aegina, Greece. The resulting Generic DRASTIC, Pesticide DRASTIC and SI vulnerability maps indicated that the most vulnerable regions, occupying 17.0%, 20.5% and 19.3% of the study area, respectively, are located in the northwestern (Aegina town) and north (Vagia and Souvala) parts of the island. These areas are characterized by highly permeable limestones and shallow water table.

The results of the single-parameter sensitivity analysis indicated that the topography (T) and the impact of the vadose zone (I) were the most significant Generic and Pesticide DRASTIC parameters, while aquifer media (A) was the most influential parameter in the SI vulnerability approach followed by land use (LU) and topography (T).

Groundwater vulnerability maps were validated using actual concentrations of nitrates in groundwater for the entire study area, and the results showed fairly good to almost very good positive correlation (correlation coefficients 0.679, 0.748 and 0.563) for the Generic DRASTIC, Pesticide DRASTIC and SI indices respectively, thus indicating that the Pesticide DRASTIC model is characterized by very good accuracy.

The integrated methodology adopted in this study (creation of maps, sensitivity analysis and validation) is particularly accurate and reliable in terms of delineating the most vulnerable areas that require in-depth and frequent monitoring. Therefore, this approach can be a useful tool for policy makers during the implementation and prioritization of policies for groundwater protection and management, especially in areas where intensive agricultural activities in terms of water consumption and use of agrochemicals are carried out.

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