

Groundwater vulnerability assessment of a coastal aquifer system at River Nestos eastern Delta, Greece

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Abstract Processes such as urbanization, agricultural development and industrialization have led to increasing demand of groundwater resources resulting in pollution threats to groundwater in different ways, either as contaminant loads on the ground surface, or as seawater intrusion due to overexploitation of wells in the coastal zone. Two groundwater vulnerability indices are applied in this paper to assess the potential risk of groundwater contamination in the eastern delta of Nestos River, Greece. DRASTIC model is used in this paper to evaluate the groundwater vulnerability of the area with focus on agrochemical contaminants, more especially on nitrate pollution, since the region is highly cultivated. Additionally, GALDIT index is also applied to assess the vulnerability of the freshwater aquifer to seawater intrusion, as the extensive pumping of the coastal wells has led to this phenomenon. The vulnerability assessment showed that the study area experiences low to moderate groundwater vulnerability to agrochemical contaminants, as well as moderate to high vulnerability to seawater intrusion. The use of GIS for both vulnerability indices was found effective for the evaluation of each method in comparison to real field data.

Keywords DRASTIC · GALDIT · Vulnerability index · Coastal hydrogeology · Groundwater pollution · Seawater intrusion · Coastal aquifer management

Introduction

Today millions of people worldwide rely on groundwater to meet their daily water needs. However, this precious resource has been threatened by overexploitation and mismanagement practices that take place globally, leading very often to seawater intrusion in coastal areas. Processes such as urbanization, agricultural development and industrialization have led to increasing demand of groundwater resources, given that surface water is exposed to higher contaminants load, hence expensive treatment is usually necessary.

This study aims at the assessment of groundwater vulnerability in the eastern delta of Nestos River, northeastern Greece (Fig. 1), where the intensive agricultural activities have proved to be the main cause of groundwater pollution in the region. The extensive pumping of the coastal wells has led to the intrusion of seawater towards the mainland freshwater porous aquifer.

For such investigation, two groundwater vulnerability indices are applied, using Geographic Information System (GIS), to assess the current hydrogeological conditions of the aforementioned area with respect to the potential risk of groundwater contamination. DRASTIC model is used to evaluate the groundwater vulnerability of the area with focus on agrochemical contaminants, more especially on nitrate pollution, since the region is highly cultivated. Additionally, GALDIT index is applied to assess the vulnerability of the freshwater aquifer to seawater encroachment.

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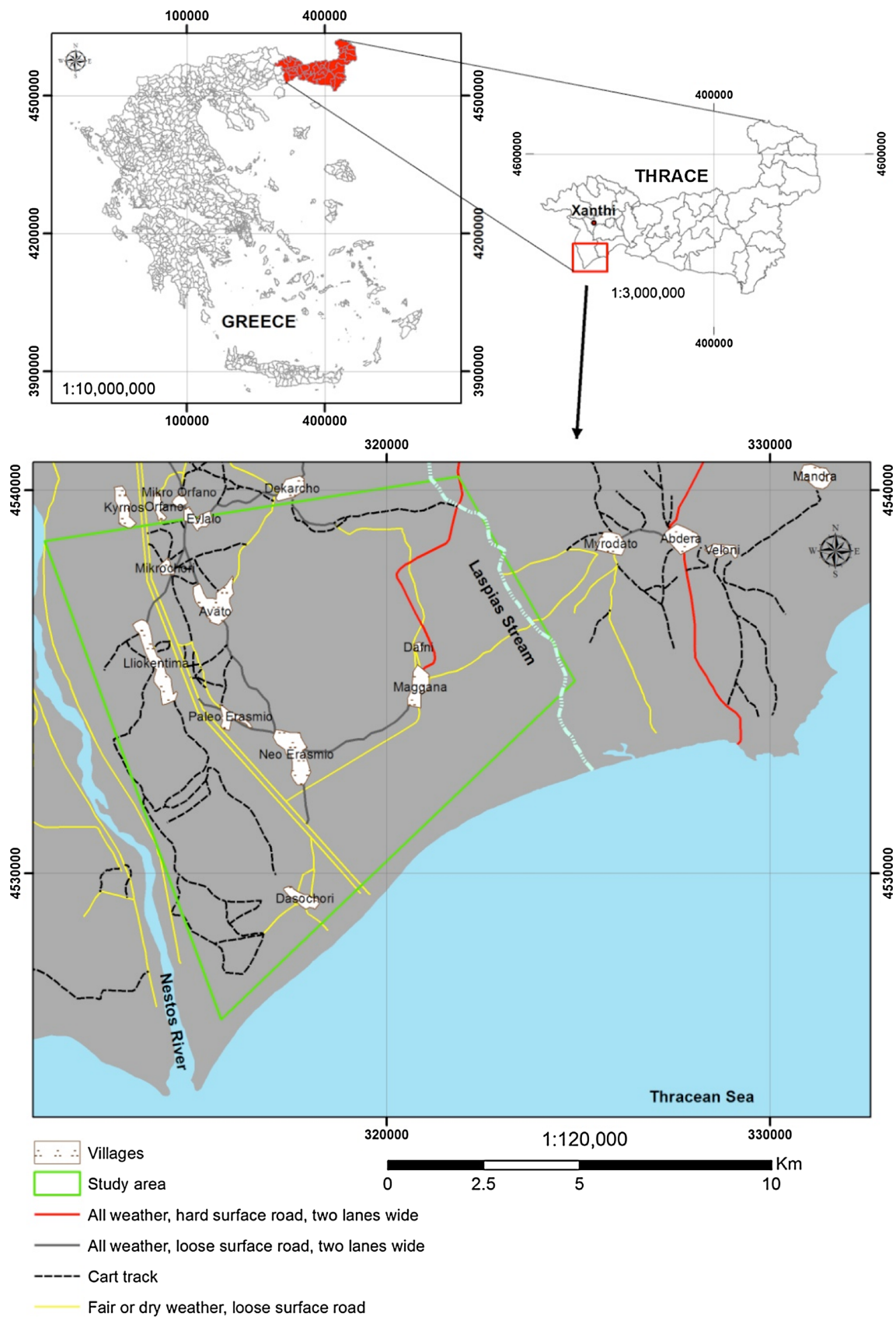


Fig. 1 Location of the study area (modified from Topographical Map of Avdera—HAGS 1970)

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 (Panagopoulos et al. 2006). The DRASTIC method is a familiar method developed in the US Environmental Protection Agency (USEPA) by Aller et al. (1987) and this method has been applied in several regions by different researchers (Sener et al. 2009). DRASTIC standardized model (Aller et al. 1987) targets the groundwater protection through the evaluation of the groundwater pollution potential in any hydrogeological scenery. The final product is addressed to decision makers, administrators and authorities to support the assessment of the groundwater vulnerability to different sources of contamination.

There are two different versions for DRASTIC, the original one and the modified pesticide version, with some hydrogeological factors having a little different weight. The two versions of DRASTIC are based on four assumptions:

1. The pollutant is introduced at the ground surface.
2. The pollutant is flushed into the groundwater by precipitation.
3. The pollutant has the mobility of water.
4. The minimum area evaluated by DRASTIC is 0.40 km².

The seven most important parameters from which the name of the model is derived are **D**epth to water table, **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone and **H**ydraulic Conductivity. Normally, these data are easily obtained and describe well the study area in hydrogeological means. DRASTIC method is also composed of a numerical ranking system, which is used to assess the groundwater pollution potential for each of the seven variables mentioned above. This system has three components: weights, ranges and ratings. A relative weight between 1 and 5 is assigned for each parameter, being 5

considered the most significant regarding contamination potential and 1 being least significant (Table 1).

In turn, numerical ranges or media types, which influence pollution potential, are given to each hydrogeological parameter. Then, the ratings are used to quantify the ranges/media concerning the possibility of groundwater contamination. By the end, all information is computed in the following simple equation:

$$\text{DRASTIC index} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where *D*, *R*, *A*, *S*, *T*, *I*, *C* are the seven variables, and the subscripts *r* and *w* denote rating and weight, respectively. The numerical index provides an indication of a certain area to be more susceptible to groundwater contamination relative to one another in a specific site. The higher the DRASTIC index, the greater is the vulnerability of the aquifer to pollution.

In DRASTIC system, the weight has to be constant, while the ranges and ratings can be altered according to the hydrogeological conditions which the investigated area possesses. It is worth to mention that DRASTIC index is a relative assessment tool and it does not replace in situ measurements. Moreover, the flexibility to modifications and adjustments is one of the most distinctive characteristics of DRASTIC model.

Several case studies of DRASTIC methodology are reported worldwide, demonstrating how functional the model is for different sources of pollution, as follows: agricultural activities (Akhavan et al. 2011; Al-Zabet 2002; Almasri 2008; Ehteshami et al. 1991; Ettazarini 2006; Jamrah et al. 2007; Mishima et al. 2010; Neshat et al. 2014; Thirumalaivasan et al. 2003; Tilahun and Merkel 2010; Yin et al. 2013), industrial activities (Johansson et al. 1999; Kalinski et al. 1994), mining activities (Bukowski et al. 2006), urban activities (Fritch et al. 2000; Hentati et al. 2010; Monteiro et al. 2008; Rosen 1994; Wen et al. 2008) and other general human activities (Al-Hanbali and Kondoh 2008; Baalousha 2006; El Naqa 2004; Ettazarini and El Mahmoudi 2004; Metni et al. 2004; Pathak et al. 2008; Shahid 2000; Voudouris and Mandilaras 2004). There are also some worth mentioning modified DRASTIC model studies for evaluating karst and fractured aquifer systems (Denny et al. 2007; Mimi and Assi 2009).

On the other hand, GALDIT vulnerability model assesses the potential risk of seawater intrusion in hydrogeological scenarios. The most significant variables controlling seawater intrusion are: **G**roundwater occurrence (aquifer type; unconfined, confined and leaky confined), **A**quifer hydraulic conductivity, **D**epth to groundwater **L**evel above sea, **D**istance from the shore (distance inland perpendicular from shoreline), **I**mpact of existing status of seawater intrusion in the area, **T**hickness of the aquifer

Table 1 Assigned weights for DRASTIC and modified pesticide DRASTIC parameters (Aller et al. 1987)

Parameter	Weight (original version)	Weight (modified pesticide)
Depth to water table	5	5
Recharge	4	4
Aquifer media	3	3
Soil media	2	5
Topography	1	3
Impact of the vadose zone	5	4
Hydraulic Conductivity	3	2

which is being mapped. The highlighted initial letters form the acronym GALDIT, and these six parameters characterize measurable variables for which data are generally accessible from a variety of sources without detailed investigation.

GALDIT indicator model also consists of a numerical ranking system to evaluate seawater intrusion potential in hydrogeological settings for each of the six parameters aforementioned. The system has three different parts: weights (Table 2), ranges, and ratings (Chachadi and Lobo Ferreira 2001).

Each of the six variables has a pre-determined fixed weight that reflects its relative importance to seawater intrusion, being four considered the most important regarding seawater encroachment potential and one being least significant. Then, GALDIT index is computed through the multiplication of the rating attributed to each parameter by its relative weight and adding up all six products, according to the expression:

$$\text{GALDIT index} = \frac{\sum_{i=1}^6 \{(W_i)R_i\}}{\sum_{i=1}^6 W_i} \quad (2)$$

where W_i is the weight of the i th indicator and R_i is the importance rating of the i th indicator. *G*, *A*, *L*, *D*, *I* and *T* are the importance ratings of factors involved in GALDIT vulnerability index and the numerical coefficients are the weights. In general, the lower the GALDIT index, the lesser is the vulnerability of the aquifer to seawater intrusion.

Therefore, GALDIT indicator model is applied to an area of interest using its hydrogeological information and choosing ratings related to the specific conditions within the area, regarding seawater intrusion. Thus, it is possible to delineate zones that are more prone to seawater encroachment than other areas. It is important to mention that GALDIT index is a relative tool and it does not exclude the need for more detailed field investigations.

GALDIT index has been applied in several studies to assess the aquifer's vulnerability to seawater intrusion (Chachadi and Lobo Ferreira 2001; Chachadi et al. 2002;

Table 2 Assigned weights for GALDIT factors (Chachadi and Lobo Ferreira 2001)

Factor	Weight
Groundwater occurrence (aquifer type)	1
Aquifer hydraulic conductivity	3
Height of groundwater Level above sea level	4
Distance from the shore	4
Impact of existing status of seawater intrusion	1
Thickness of aquifer being mapped	2

Chachadi 2005; Kallioras et al. 2011; Kalyana Sundaram et al. 2008; Mahesha et al. 2012; Lobo Ferreira et al. 2005; Saidi et al. 2013; Shetkar and Mahesha 2011; Sophiya and Syed 2013; Yogesh 2005; Recinos et al. 2014).

General description of the study area

Geographical characteristics

The region of interest is located at southwest of the Xanthi Prefecture, in Thrace Region, northeastern Greece (Fig. 1). The physical boundaries of the area are the Dekarcho, Evlalo and Kyrnos villages at north, the Nestos River bed at west, the coastline at south and the Laspias Stream at east (Fig. 1), covering an area of 109 km². The geomorphology of the coastal region is characterized by low relief, predominantly flat, with the deposition of continental sediments transported by the river in the delta plain. The elevations range from the sea level to 180 m above sea level to the northeast, outside of the research area. The maximum altitude within the study area is approximately 20 m above sea level at the northeastern part. The area is mainly used for agricultural purposes (Fig. 2), a fact which is also the main reason for the groundwater quantitative and qualitative degradation.

Geological setting

Most of the investigated area lies on Holocene alluvial deposits of Nestos River, mainly composed of clay, sandy clay, sand and pebbles. Sands of the palaeo-channels of the Nestos River are found at the western boundary of the area. Silt of lacustrine facies occurs together with recent coastal deposits along the coastline in the south. Some intercalations of red clay and sand of Pliocene–Pleistocene epoch are found at the northeast margin of the study area. An inferred fault of direction northwest–southeast demarcates the area to the east, and along with the Nestos River bed to the west and the coastline to the south, enclose the hydrogeologic setting of the study area (Fig. 3). Very coarse conglomerate to micro-conglomerate (Upper Eocene–Lower Oligocene) containing lenses of limestones are found towards the northeast, outside of the area. Intrusive, metamorphic and volcanic rocks related to South Rhodope Range crop out in that direction and are strongly controlled by Tectonism (Fig. 3). The well geological logs of the research area show a typical delta depositional environment, with inverse type or prograded sequences, which occur when the delta moves towards the sea, depositing coarse sediments over the finer sediments in several repeated sequences, known as deltaic cycle. These numerous sedimentological structures lead to

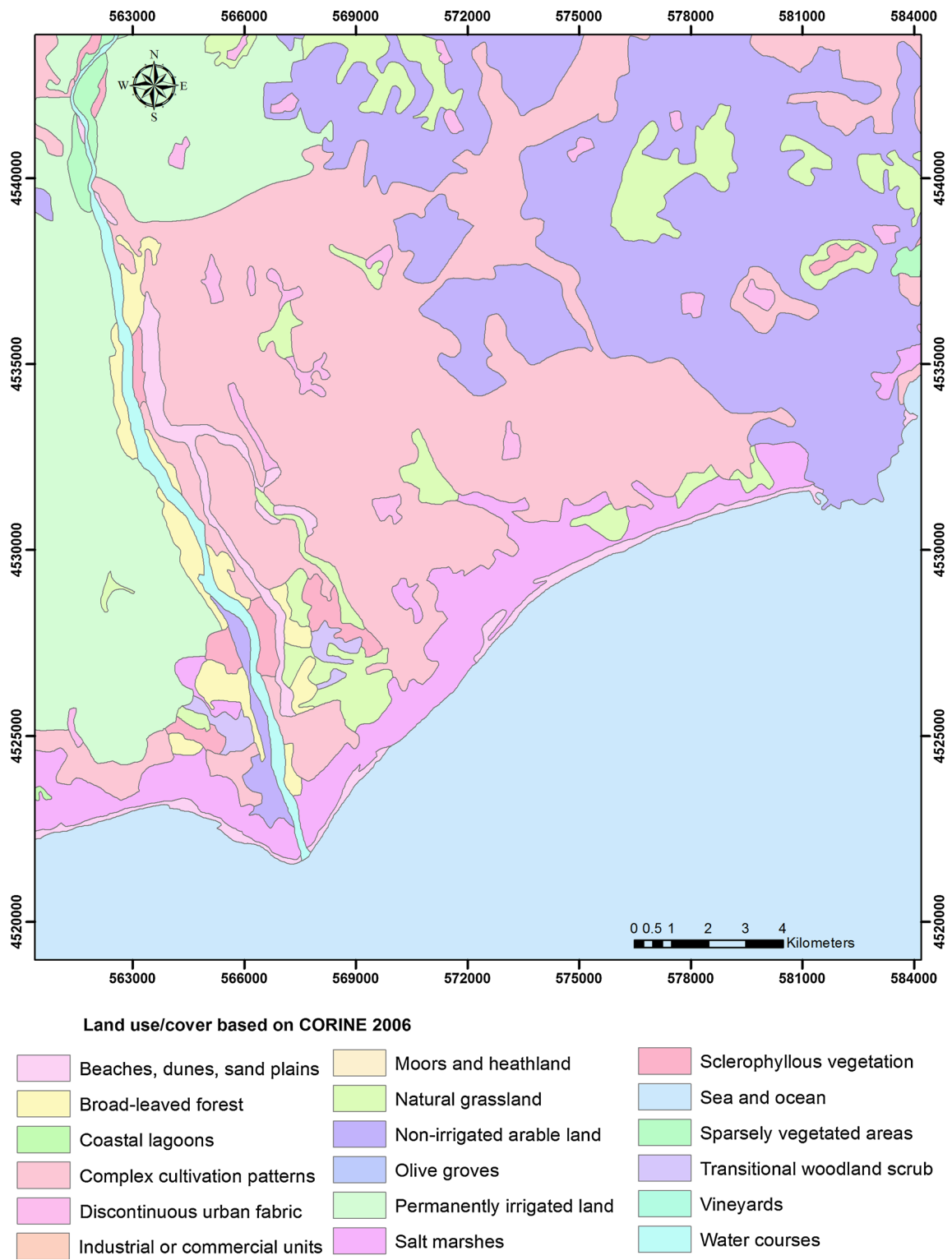


Fig. 2 Land use map of the study area (modified using Ludlow et al. 2013)

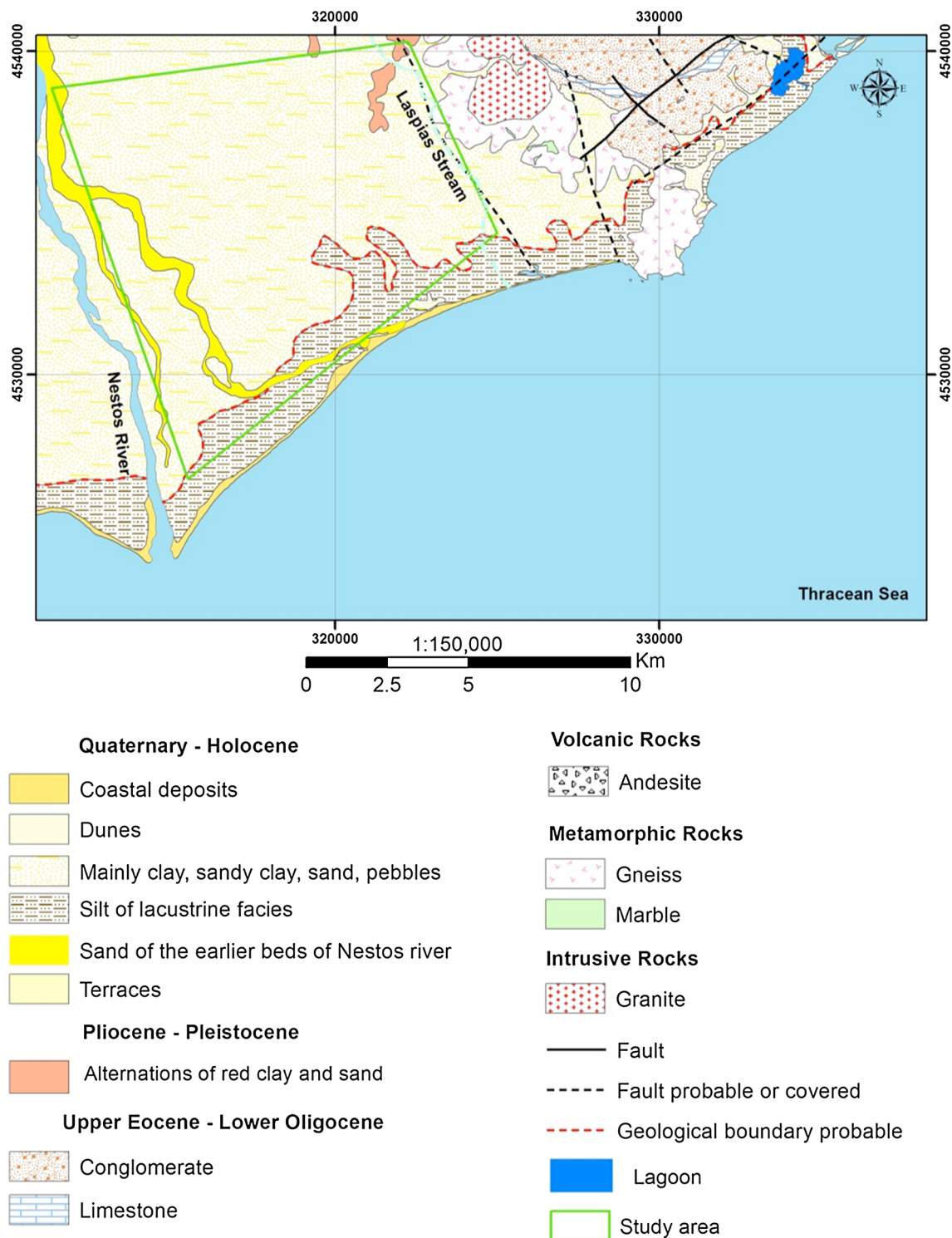


Fig. 3 Geological map of the study area (modified from geological map of Greece—IGME 1980)

highly heterogeneous environment, with a multi-layering behavior, forming phreatic aquifers as well as semi-confined to confined aquifers in the east plain of the Nestos River delta.

Hydrological conditions

In northern Greece, where the site under investigation is located, the climate is of Mediterranean type: with warm

and dry summers as well as mild and rainy winters. January is the coldest month of the year in the region with a mean temperature of 4.8 °C, and the warmest is July with a mean temperature of 23.6 °C (Xeidakis et al. 2010).

The high temperatures recorded during the summer in the study area cause a moisture deficit, especially at the agricultural fields as the evapotranspiration increases significantly, leading to a rise of the demand for groundwater for irrigation purposes. The latter, in combination with overexploitation of the aquifers, have resulted in seawater intrusion and consequently salinization of soils and fresh groundwater.

Table 3 presents a comparative average, minimum and maximum precipitation recorded over the period of 4 decades (1966–2006). December is the wettest month of the period, with maximum precipitation of 482 mm, while all months show no precipitation as minimum value, except March which recorded a minimum of 5 mm. It is noticed through the graph that the precipitation is relatively low in the study area, which contributes to the great necessity of groundwater resources for agricultural activities. The groundwater is so excessively abstracted leading to seawater encroachment and degradation of its quality.

Hydrogeological conditions

According to Sakkas et al. (1998), there are two main hydrogeologic systems composed of alluvial deposits in the east plain of the Nestos River delta: the shallow unconfined aquifer and the underlying deeper one. The shallow system is phreatic and/or semi-confined at certain parts extended down to a depth of approximately 30 m. This system is naturally recharged by direct infiltration from rainfall and less by stream bed percolation from the north hilly area. During the last decade, a significant amount of small diameter shallow wells (down to 15 m depth) are pumping groundwater from the unconfined aquifer system. Nowadays, only few of them are operated, whilst many have been replaced by deeper wells (up to 50 m depth), as it is seen in Dekarchon area. In turn, the deep system is composed of confined aquifers extended to a depth of at least 190 m. Natural recharge to this system comes to a great extent from Nestos River percolation through buried old stream beds, and from the lateral groundwater inflows coming from the adjoining Vistonis lagoon hydrogeologic

basin. There are 50 deep wells (down to 200 m depth), located in the main study area.

Additionally, a karst domain located upstream of Nestos River, almost 25 km to the northwest, also contributes to the groundwater recharge of the deeper hydrogeological system.

Gkiougkis et al. (2011) describe the basic groundwater hydrological balance, as follows:

- The east delta plain extends to 176.4 km², from which the 106.63 km² are cultivated (only 60 %), while the coastal saline uncultivated lands extend to 45 km². Considering the hydrological data of Nestos Delta plain (mean annual rainfall for the period 1965–1996: 546.9 mm, infiltration approximately: 15 %), the annual infiltration for the 131.4 km² area is estimated at 10.8×10^6 m³.
- The irrigated lands extend to 89.90 km², while the 35 km² of them meet irrigation needs from the Nestos River. The rest areas meet irrigation needs by pumping, where considering the type and the extent of the crops as also as well operation data, the annual water consumption is estimated approximately at 27×10^6 m³.
- Taking into account the amounts of the two basic parameters of the groundwater hydrologic balance mentioned above (infiltration-water consumption), a lack of app. 16×10^6 m³ water is evaluated (Pliakas et al. 2001; Sakkas et al. 1998).
- It is estimated that a small part of this lack is compensated by the Nestos riverbed percolation, at rates depending on the flow of the buried old streambeds and the distance from the river (Gkiougkis et al. 2010, 2014).

Figures 4 and 5 show the piezometric maps of the upper unconfined aquifer system of the investigated area before and after the irrigation period. The first map of October 2008 refers to the end of the dry season, i.e., after the irrigation period, while the map of April 2009 displays the piezometric conditions after the wet season, i.e., before the irrigation period. Both maps present the major groundwater flow direction from north-northwest to south-southeast with minor flow from northeast and central parts towards the south. The piezometric contours are similar on both maps indicating that the groundwater flow regime does not change significantly during the seasons of the year.

Table 3 Average, minimum and maximum precipitation data (1996–2006)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
MIN	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAX	152.5	225.0	222.0	120.5	119.0	120.0	152.0	193.2	132.6	149.4	211.5	482.0
AVE	53.7	55.4	47.6	42.5	43.4	39.5	34.4	25.1	35.6	49.7	73.3	101.8

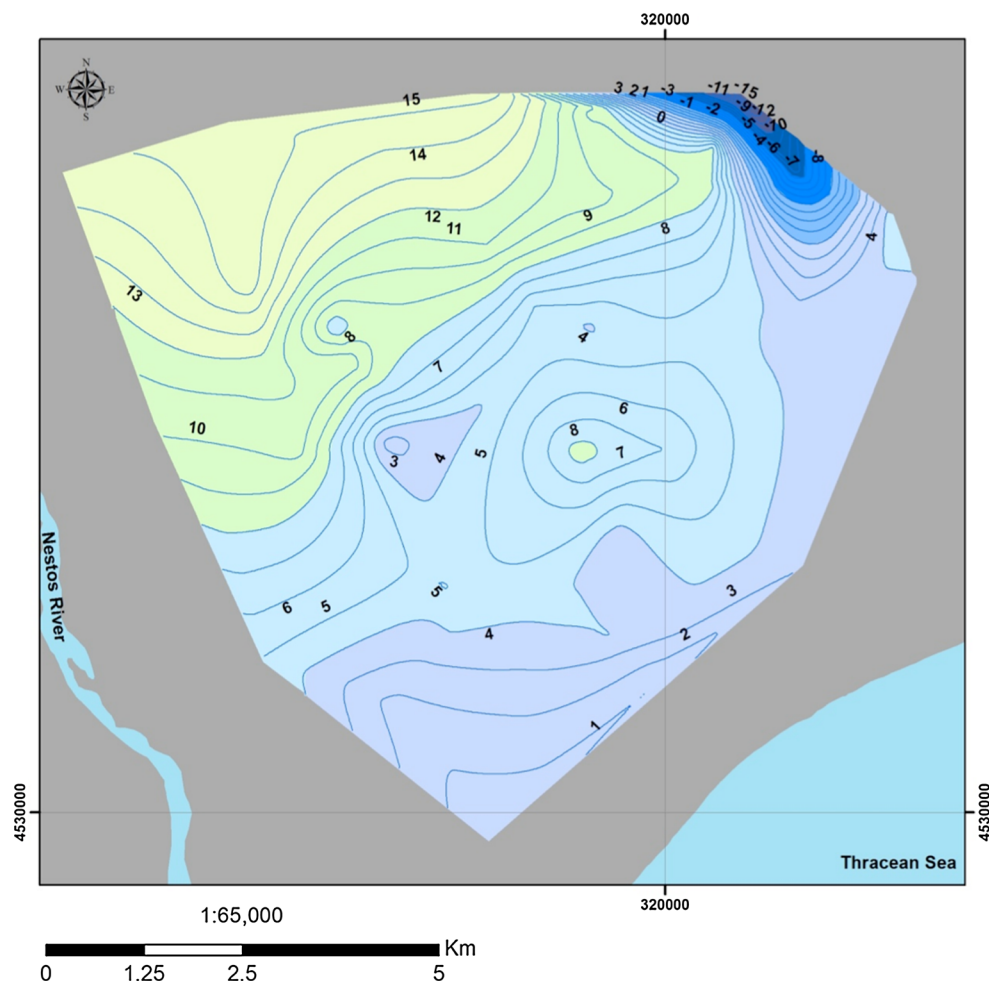


Fig. 4 Piezometric map of the upper unconfined aquifer system (October 2008)

DRASTIC

Introduction

The DRASTIC vulnerability index for the study area of eastern Nestos delta was produced after individual analysis of 43 monitoring wells evenly distributed within the investigated area. Each well contains a categorization of the DRASTIC parameters as result of weighting, ranging and rating. For this categorization, a set of geologic, hydrologic, hydrogeologic and morphologic data was used as well as single parameter maps were produced displaying the rating values. Complementary wells and boreholes were utilized with chemical and geological data, as well as information from literature like infiltration rate and thickness of the aquifer was employed in the investigation. Finally, the DRASTIC vulnerability index (DVI) of each well was synthesized in final maps of the groundwater vulnerability index distribution.

Depth to water table (D)

This parameter assesses the distance from the ground surface to the water table through which a pollutant travels before reaching the aquifer. The shorter the depth to water table, the more vulnerable is the aquifer to contamination. The groundwater depth values used for the 43 wells (Gkiougkis et al. 2011, 2014) refer to the piezometric data of April 2009, at the end of the wet season and, thus, prior irrigation period.

According to DRASTIC index, the depth to water table data was adjusted into the ranges and ratings defined by Aller et al. (1987), assigning rates ranging from 1 (lowest vulnerability impact) to 10 (highest vulnerability impact) to each well (Table 4).

As the north/northeastern part is an area of higher topographical elevation (Figs. 6, 7), the groundwater table is deeper and, therefore, DRASTIC ratings range from 3 to 7. The deeper the water table within the region, the longer

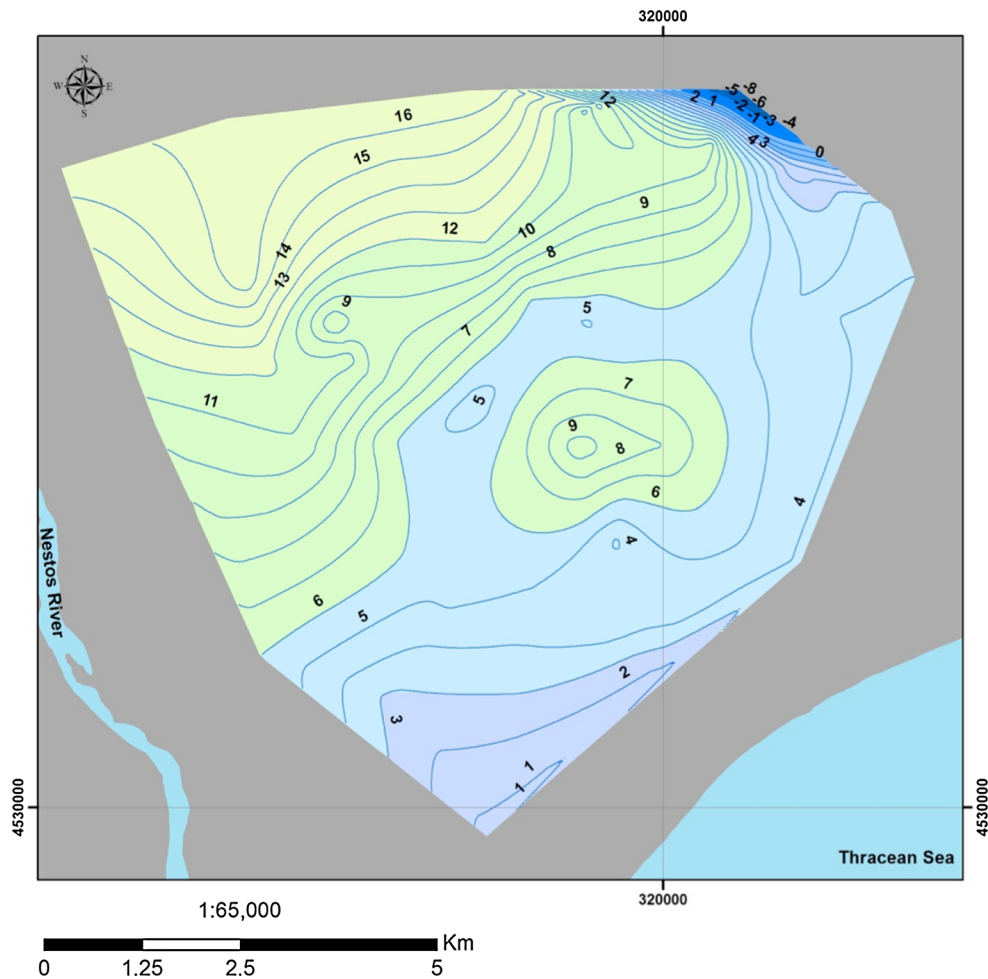


Fig. 5 Piezometric of the upper unconfined aquifer system (April 2009)

Table 4 Ranges and ratings for depth to water table (Aller et al. 1987)

Range	Rating
Depth to water table (m)	
0–1.50	10
1.50–4.50	9
4.50–9.00	7
9.00–15.00	5
15.00–22.50	3
22.50–30.00	2
30.00+	1

is the downward movement of the contaminant before it reaches the water table and, consequently, the lower is the vulnerability in this area.

On the other hand, the rest of the area falls under rating 9 and 10, with the exception of the southeastern part which has a rating of 7 (Fig. 7), as the shallower the groundwater

table, the higher is the susceptibility of the aquifer to pollution.

Net recharge (R)

Net recharge corresponds to the annual total amount of water which penetrates the ground surface and reaches the aquifer. The higher the recharge, the more vulnerable is the aquifer system to contamination, as infiltration enhances the transport and leaching of contaminants downwards to the saturated zone. According to Gkiougkis et al. (2014), the hydrological data of Nestos River delta show a mean annual rainfall of 546.9 mm for the period of 3 decades (1965–1996). Considering the area of the eastern delta (176.4 km²), excluding the area of uncultivated saline lands (45 km²) and an infiltration of 15 %, the annual amount of infiltrated water of 10.8×10^6 m³ is estimated for an area of 131.4 km².

The net recharge for the investigated site was classified into the ranges defined for this parameter by the DRASTIC

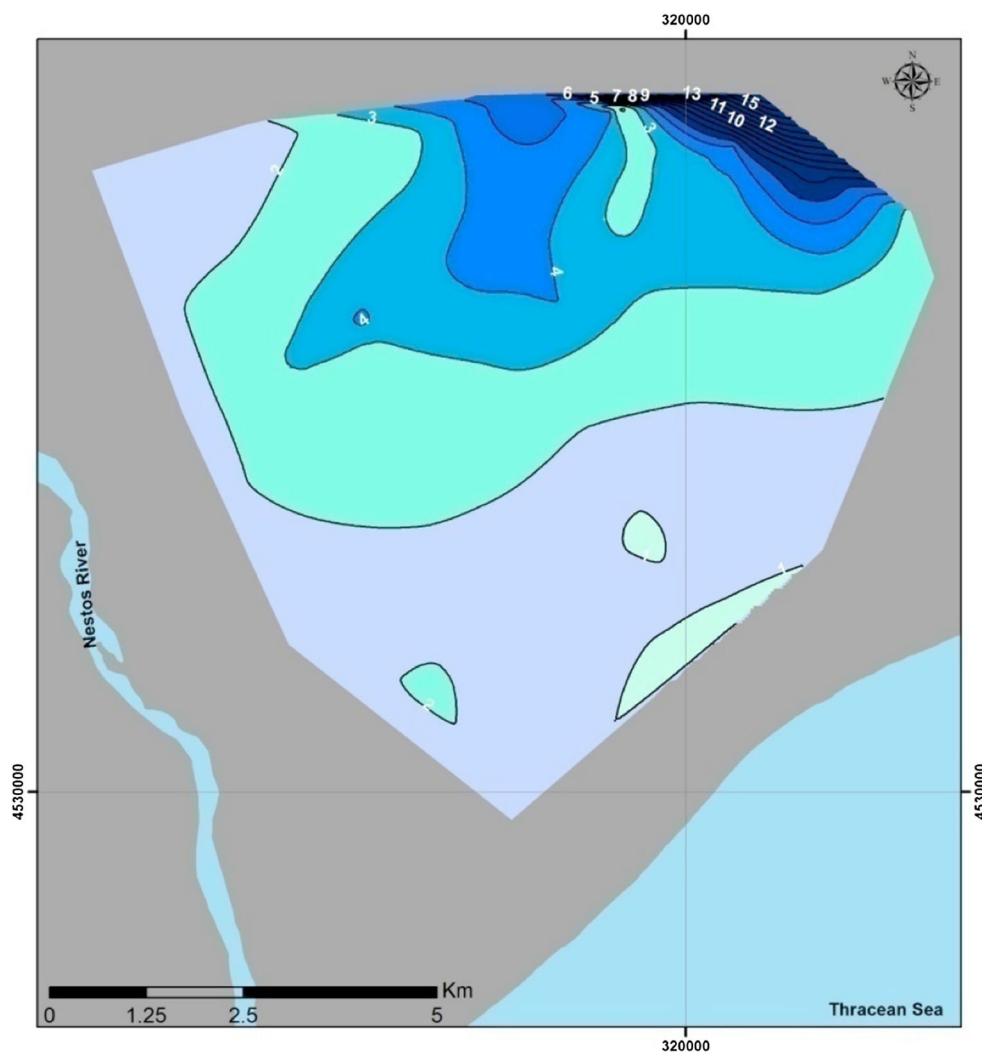


Fig. 6 Depth to water table distribution in meters (April 2009)

method, assigning rates ranging from 1 to 10, i.e., from minimum to maximum vulnerability impact, respectively (Table 5). The climatic characteristics of the study area as well as its soil coverage can be considered homogeneous for the entire area; therefore, the rating given to this parameter is 3 for all wells (Table 5), since the mean recharge of the area is 82.035 mm/year (546.9 mm/year \times 15 %).

Aquifer media (A), soil media (S) and impact of the vadose zone (I)

The aquifer medium represents the consolidated or unconsolidated material through which the water percolates downwards. Generally, the larger the grain size, the higher is the porosity of the aquifer formation and hence the higher is the vertical hydraulic permeability; consequently, the higher aquifer vulnerability. After

detailed analyses of the geological map and monitoring boreholes installed in the study area, it was proved that the aquifer media consists of sand, clay and gravel, falling under the rating 5 according to DRASTIC model (Table 6).

The soil media parameter corresponds to the uppermost portion of the unsaturated zone and it constitutes an important factor controlling the infiltration rates within the vadose zone until reaching the water table. The larger the amount of finer particles in the soil and the thicker the soil layer, then the higher is the capacity of attenuation of pollutants and, thus, the lower is the vulnerability. The boreholes installed in the study area provided the soil cover information for the surrounding of the observation wells. The soil cover is composed of sand, clayey sand, sandy clay, black clay and gravel. The ratings (Table 7) then varied among 3 (sandy clay), 6 (clayey sand), 7 (black clay), 9 (sand) and 10 (gravel).

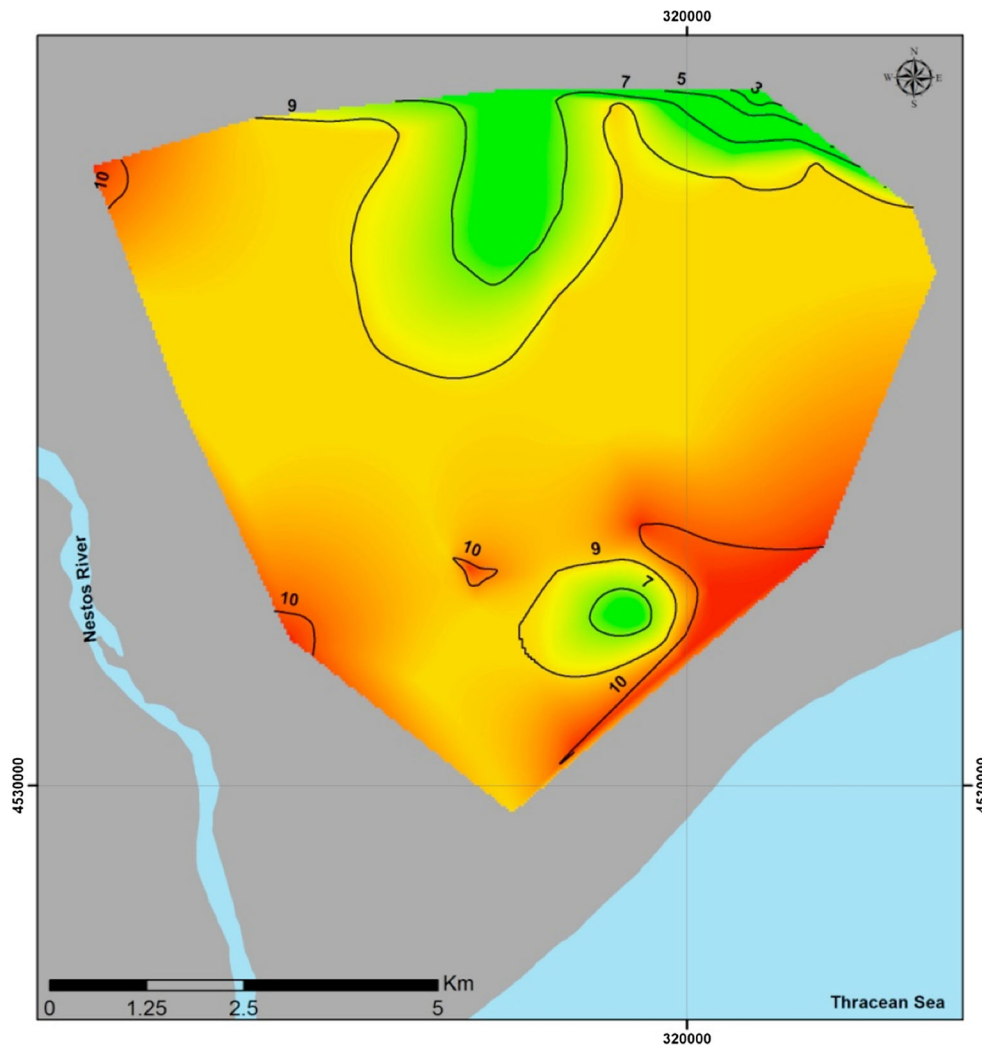


Fig. 7 Categorization of depth to water table after DRASTIC rating values (April 2009)

Table 5 Ranges and ratings for net recharge (Aller et al. 1987)

Range	Rating
Net recharge (cm)	
0–5.00	1
5.00–10.00	3
10.00–17.50	6
17.50–25.00	8
25.00+	9

The material of which the vadose zone is composed determines the confining conditions or the pathway through which the contaminant is transported before it reaches the aquifer. In the case of this study, the vadose zone parameter was defined through the analysis of the boreholes and the geological map of the area. The vadose zone is

characterized mostly by sand, sandy clay and clayey sand, corresponding to ratings of 7, 4 and 5, respectively (Table 8).

Topography (T)

This parameter incorporates the slope of the land surface. The topographic characteristics of the terrain directly affect the surface runoff of the contaminant or its infiltration towards the subsurface. Thus, steeper slopes lead to higher runoff of contaminants and, consequently, lower potential for groundwater pollution. The geomorphology of the investigated area is predominantly flat with low relief, which can be observed in the Digital Elevation Model (DEM) of the region (Table 9; Fig. 8).

The above elevation of the area corresponds to a rating value of 10 for the DRASTIC index (Table 10).

Table 6 Ranges and ratings for aquifer media (Aller et al. 1987)

Range	Rating
Aquifer media	
Massive shale	1–3
Metamorphic/igneous	2–5
Weathered metamorphic/igneous	3–5
Glacial till	4–6
Bedded sandstone, limestone and shale sequences	5–9
Massive sandstone	4–9
Massive limestone	4–9
Sand and gravel	4–9
Basalt	2–10
Karst limestone	9–10

Table 7 Ranges and ratings for soil media (Aller et al. 1987)

Range	Rating
Soil media	
Thin or absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or aggregated clay	7
Sandy loam	6
Loam	5
Silty loam	4
Clay loam	3
Muck	2
Non shrinking and non aggregated clay	1

Hydraulic conductivity (C)

Hydraulic conductivity controls the rate of groundwater flow through an aquifer system. The higher the hydraulic conductivity, the higher is the vulnerability of the aquifer. The apparent horizontal hydraulic conductivity was calculated from the transmissivity (T) data of pumping tests carried out in selected boreholes within the area (transmissivity values ranging from 4.0×10^{-4} to 1.1×10^{-2} m²/s, Pliakas et al. 2001; Sakkas et al. 1998). According to Pliakas et al. (2001), the shallow aquifer system extends down to a depth of approximately 30 m.

Considering an average of 3 m depth for the water table in the phreatic system, an average saturated thickness of 27 m (30–3 m) was found to calculate the apparent horizontal hydraulic conductivity. The latter is represented by the equation:

$$K_{hA} = T_t/D_t \quad (3)$$

Table 8 Ranges and ratings for impact of the vadose zone (Aller et al. 1987)

Range	Rating
Impact of the vadose zone	
Confining layer	1
Silt/clay	2–6
Shale	2–5
Limestone	2–7
Sandstone	4–8
Bedded limestone, sandstone, shale	4–8
Sand and gravel with significant silt and clay	4–8
Metamorphic/igneous	2–8
Sand and gravel	6–9
Basalt	2–10
Karst limestone	8–10

Table 9 Ranges and ratings for topography (Aller et al. 1987)

Range	Rating
Topography (% slope)	
0–2	10
2–6	9
6–12	5
12–18	3
18+	1

where K_{hA} is the apparent horizontal hydraulic conductivity (m/s), T_t is the transmissivity (m²/s), and D_t is the saturated thickness (m).

The hydraulic conductivity distribution map is displayed in Fig. 9.

The data were then classified into ranges and ratings of DRASTIC, assigning to each well rates ranging from 1 (lowest vulnerability impact) to 10 (highest vulnerability impact), as shown in Table 10. From the previous map, it can be observed that a zone of high hydraulic conductivity appears at the northwestern part of the study area, with values reaching 4×10^{-4} m/s. A DRASTIC rating value of 4 was assigned for this part of the study area as well as for the parts at the south and northeastern boundaries (Table 10; Fig. 10).

DRASTIC groundwater vulnerability indices

The two versions of DRASTIC (original and pesticides) were applied in the study area to compare the differences which may appear between the two indices. The pesticide version considers the parameters soil media, topography,

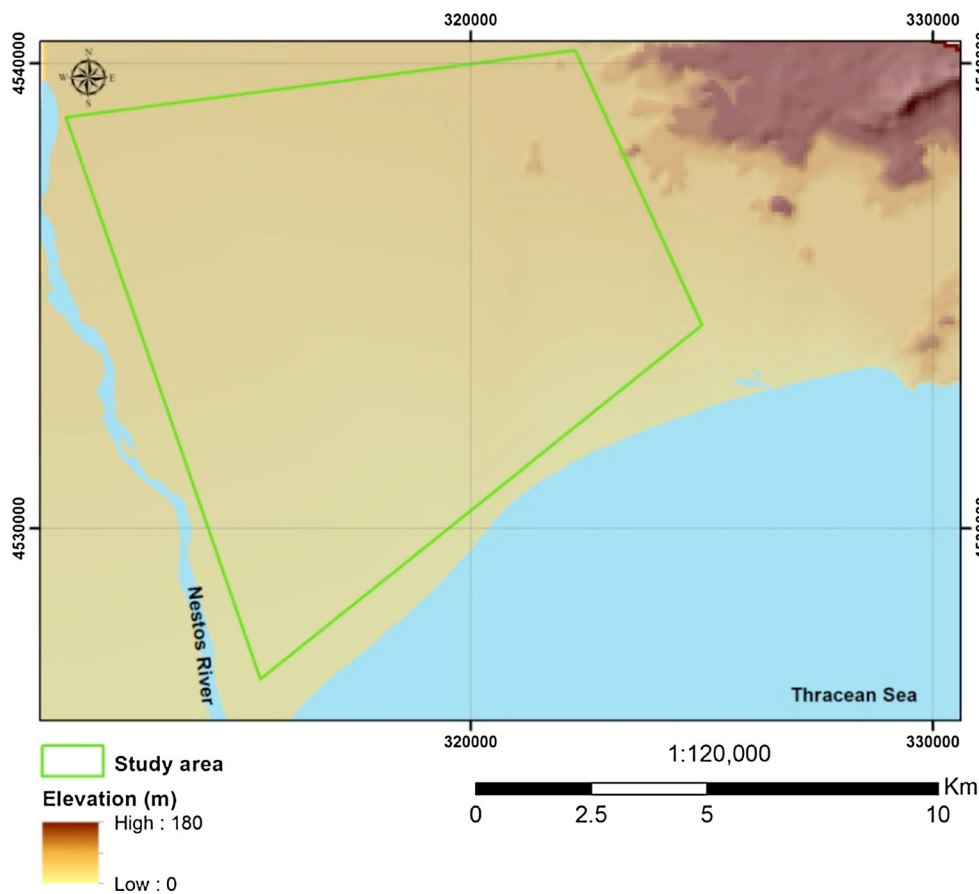


Fig. 8 Digital elevation model (DEM) of the study area

Table 10 Ranges and ratings for hydraulic conductivity (Aller et al. 1987)

Range	Rating
Hydraulic conductivity (m/day)	
0–5	1
5–15	2
15–35	4
35–50	6
50–100	8
100+	10

impact of the vadose zone and hydraulic conductivity with different weights from original version.

The vulnerability index generated for the study area presents values ranging from 90 to 130 at the northern and northeastern part of the study area, corresponding to approximately 40 % of the entire area. These values are considered as index values of low vulnerability. The values are higher towards the south and northwest, reaching 150, equivalent to approximately 60 % of the area and corresponding to moderate vulnerability index values (Fig. 11).

DRASTIC model considers that the pollution source is located onto the ground surface, from where the contaminant is flushed into the vadose zone through precipitation or irrigation return flow, infiltrating downwards until it percolates into the saturated zone and contaminates the groundwater.

Observing the pesticide vulnerability index of the study area (Fig. 12), although the contour lines distribution is basically the same, the values are higher in the pesticide version. The northern and northeastern regions show values ranging from 115 to 170, meaning moderate to high vulnerability. This range encompasses approximately 40 % of the study area. Towards the northwest, eastern and south, values ranging from 170 to 190 are found, corresponding to 60 % of the entire area. These regions fall under high vulnerability.

The Laspas Stream, located at east/northeast of the study area, constitutes a receptor of sewage treatment effluents and industrial waste from the surroundings. Besides, it also receives irrigation waters from a drainage trench located at a distance of approximately 2 km to the north. Besides the Laspas Stream, a great number of PSP (point source pollution) as stables and piggeries are found

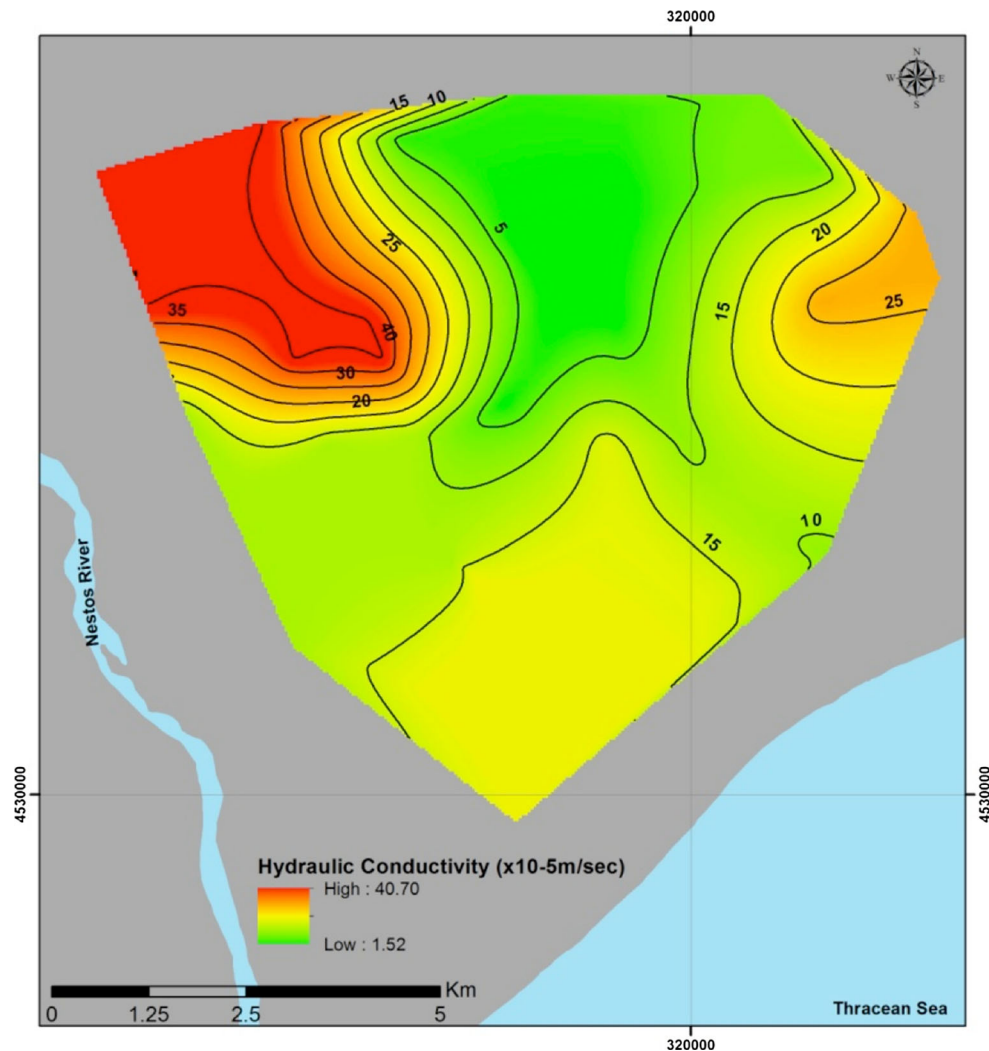


Fig. 9 Hydraulic conductivity distribution map

in the research area. All these sites form potential sources of nitrate pollution in the study area.

GALDIT

Introduction

The extensive use of groundwater for irrigation purposes in coastal aquifers is considered a cause of disturbance of the hydrodynamic balance within the transition zone between the two fluids (fresh- and saline water). The imbalance caused by the excessive pumping near the shoreline leads to the reversion of natural groundwater flow gradient towards the sea and, consequently, the seawater encroachment into the mainland. The contamination caused by seawater intrusion in coastal aquifers can be

successfully assessed by the application of GALDIT vulnerability index, which takes into account six factors indispensable to compound the hydrogeologic framework of a given area. Through the analysis of these six parameters, it is possible to analyze the degree of susceptibility of the aquifer to seawater intrusion potential.

Groundwater occurrence (G)

This parameter refers to the type of aquifer, i.e., confined, unconfined and leaky confined in a given area. According to GALDIT index, the rating values for all parameters range from 2.5 (lowest vulnerability) to 10 (highest vulnerability). As for the case of the eastern delta of Nestos River, the upper aquifer system under investigation is unconfined and, therefore, a GALDIT rating value of 7.5 was assigned for all monitoring wells (Table 11).

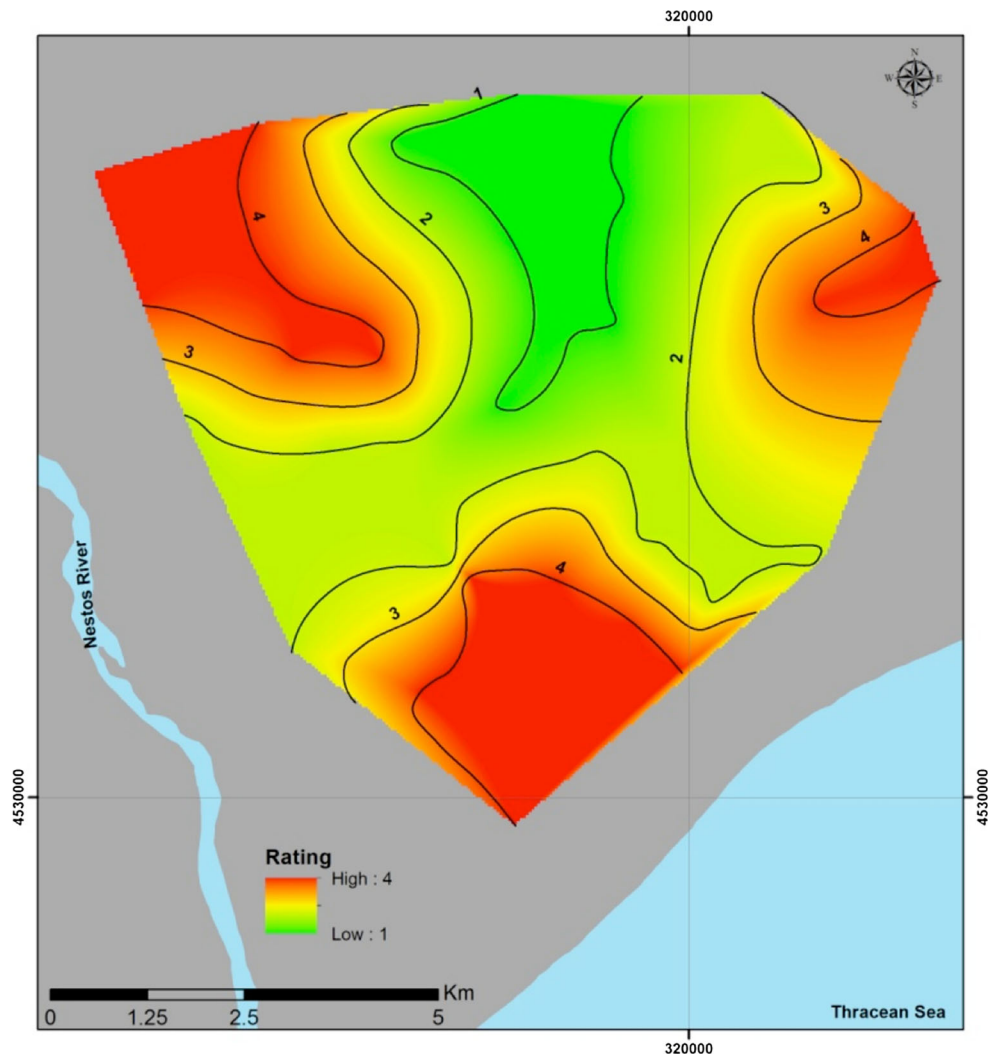


Fig. 10 Categorization of hydraulic conductivity parameter after DRASTIC rating values

Aquifer hydraulic conductivity (A)

The hydraulic conductivity is, as previously described, a property of the aquifer that expresses the water flow rate through pore spaces and fractures. Chachadi (2005) states that the extent of seawater front is influenced by the hydraulic conductivity of the aquifer, hence higher hydraulic conductivity leads to larger inland movements of the seawater front.

The hydrogeological data used for the calculation of this parameter were the same data utilized by the DRASTIC index, as previously analyzed and presented. GALDIT index refers to ratings ranging from 2.5 to 10 for minimum and maximum vulnerability impact, respectively (Table 12). The investigated area shows a region of high hydraulic conductivity at northwest, reaching 4×10^{-4} m/s. The categorization of this parameter leads

to two more vulnerable areas, at south and at east/northeast, presenting rating of 7.5 (Fig. 13).

Height of groundwater level above sea level (L)

This parameter constitutes the most important factor in the evaluation of seawater intrusion within an area, primarily because it determines the shape of the interface as well as the inland extent of the interface toe (Chachadi 2005). The Ghyben–Herzberg relation affirms that for every meter of fresh-water stored above mean sea level, a 40-m freshwater column is formed below it downward to the salt/freshwater interface.

The groundwater elevation data were classified into ranges and ratings belonging to the parameter *L* of GALDIT index, for each well. In GALDIT index, the ratings’ values range from 2.5 to 10 for lowest and highest vulnerability impact, respectively (Table 13).

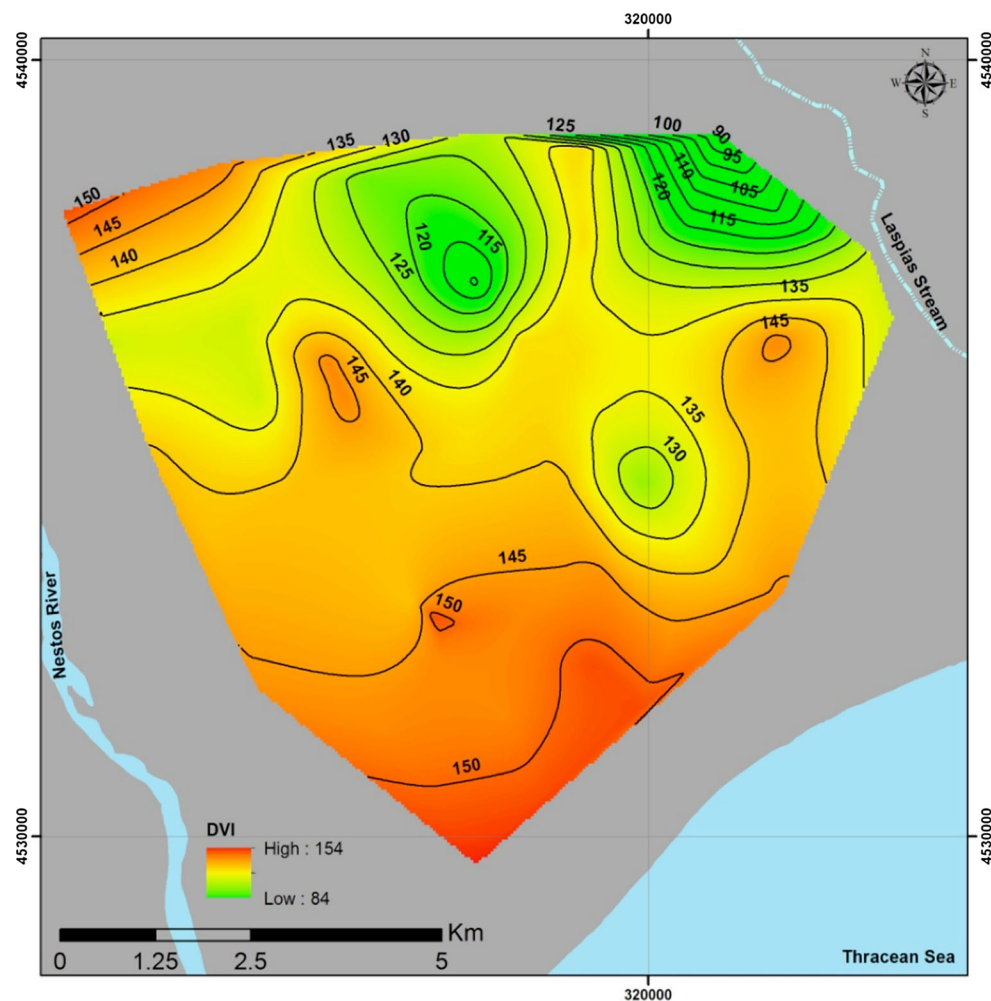


Fig. 11 DRASTIC groundwater vulnerability index (DVI) distribution map (April 2009)

The map shown in Fig. 14 displays the spatial distribution of groundwater elevation a.m.s.l. in the study area in April 2009, prior to the irrigation period. It is noticed that minimum groundwater levels above sea occur at the southern part of the area, near the shoreline, as well as at the northeastern part, where negative values are found. It is observed that the piezometric lines near the highlands of the northeastern part of the study area are lower than the areas near the coast in the southern portions due to the continuous pumping conditions that occur in that region for industrial purposes (a small paper industry that is not necessary to appear in the map).

The two critical areas were then classified into ranges from 5 to 10, according to the GALDIT index (Fig. 15). These two areas are subjects of extensive groundwater pumping and, consequently, lowering of groundwater table.

Distance from the shoreline (D)

Chloride concentration distribution data from July 2009 (Gkiougkis et al. 2014) was used for creating a modified scale of ranges of distance from the shoreline in order to achieve an improved adjustment of the D factor. Four profiles were plotted demonstrating the chloride concentrations along the distance from shoreline to the respective groundwater sampling points. As it is noticed from the chloride distribution map in groundwater, the seawater front has moved towards the mainland showing high chloride concentrations at east/southeastern part of the study area, where the highest values of chloride appear (Fig. 16).

A regression analysis was carried out to identify the trendline which provides the best fit through a set of data points from the four profiles (Figs. 17, 18).

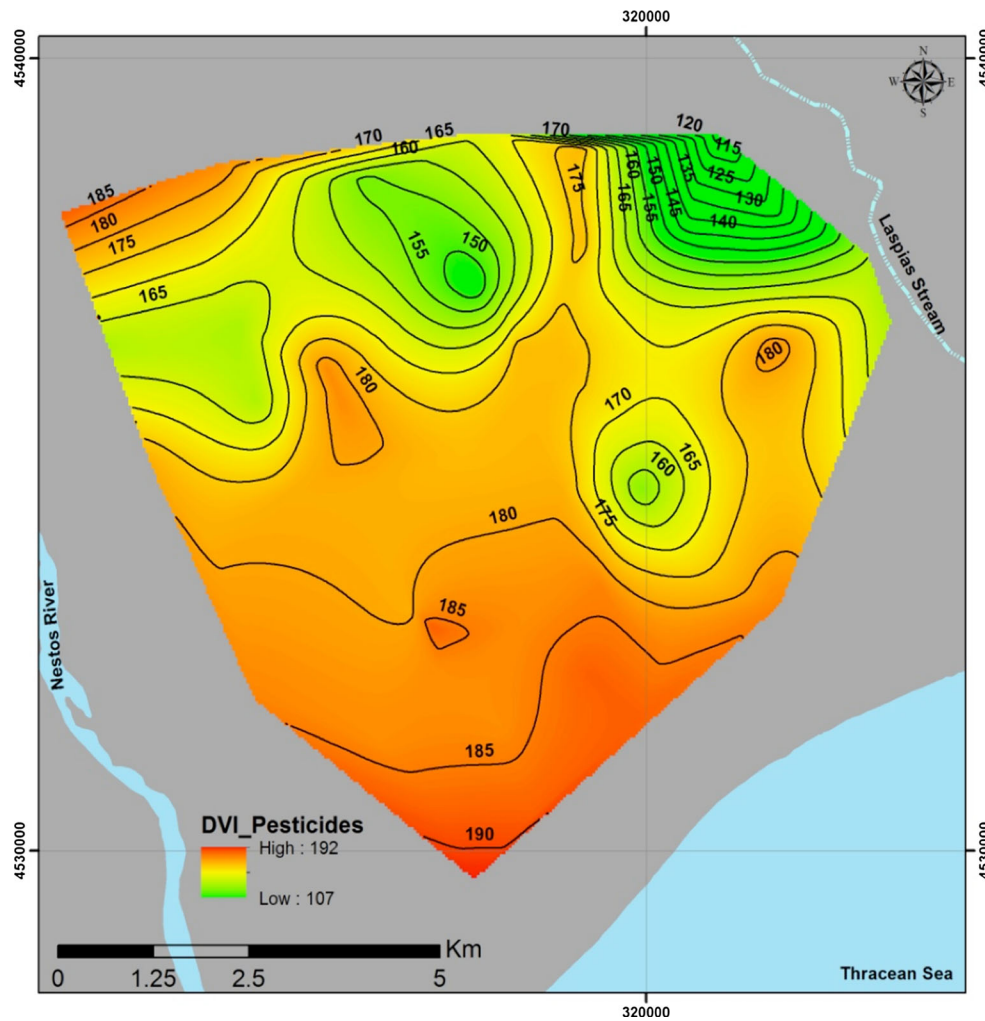


Fig. 12 DRASTIC (pesticides) groundwater vulnerability index (DVI) distribution map (April 2009)

Table 11 Ranges and ratings for groundwater occurrence (Chachadi 2005)

Range	Rating
Groundwater occurrence	
Confined aquifer	10
Unconfined aquifer	7.5
Leaky confined aquifer	5
Bounded aquifer (recharge and/or impervious boundary aligned parallel to the coast)	2.5

The profile 1 has the best regression coefficient R^2 of 0.9162, showing how well the given points can be related. Through the regression equation $y = 45650x^{-0.75}$, it was possible to determine the curve which represents the relation between chloride concentration and distance to shoreline and, consequently, the intervals which define the new range (Fig. 19).

The range is composed of four intervals which categorize the ratings for the GALDIT parameter Distance from the shoreline (D), shown in the table below (Table 14).

After the modified ranges, the distances from the monitoring points to the region considered as shoreline were measured and classified following the GALDIT rating values (minimum vulnerability impact of 2.5 and maximum vulnerability impact of 10). The categorization of this parameter depicts about 50 % of the study area as high vulnerability risk, demonstrating the importance of the factor Distance to shoreline (Fig. 20).

Impact of existing status of seawater intrusion (I)

This parameter considers an existing occurrence of seawater encroachment in a given area, which is observed from field data spatially distributed within the area of investigation. Chloride concentration values from July 2009 (Gkiougkis et al. 2014) distributed in the research

Table 12 Ranges and ratings for aquifer hydraulic conductivity (Chachadi 2005)

Range	Rating
Aquifer hydraulic conductivity (m/day)	
>40	10
10–40	7.5
5–10	5
<5	2.5

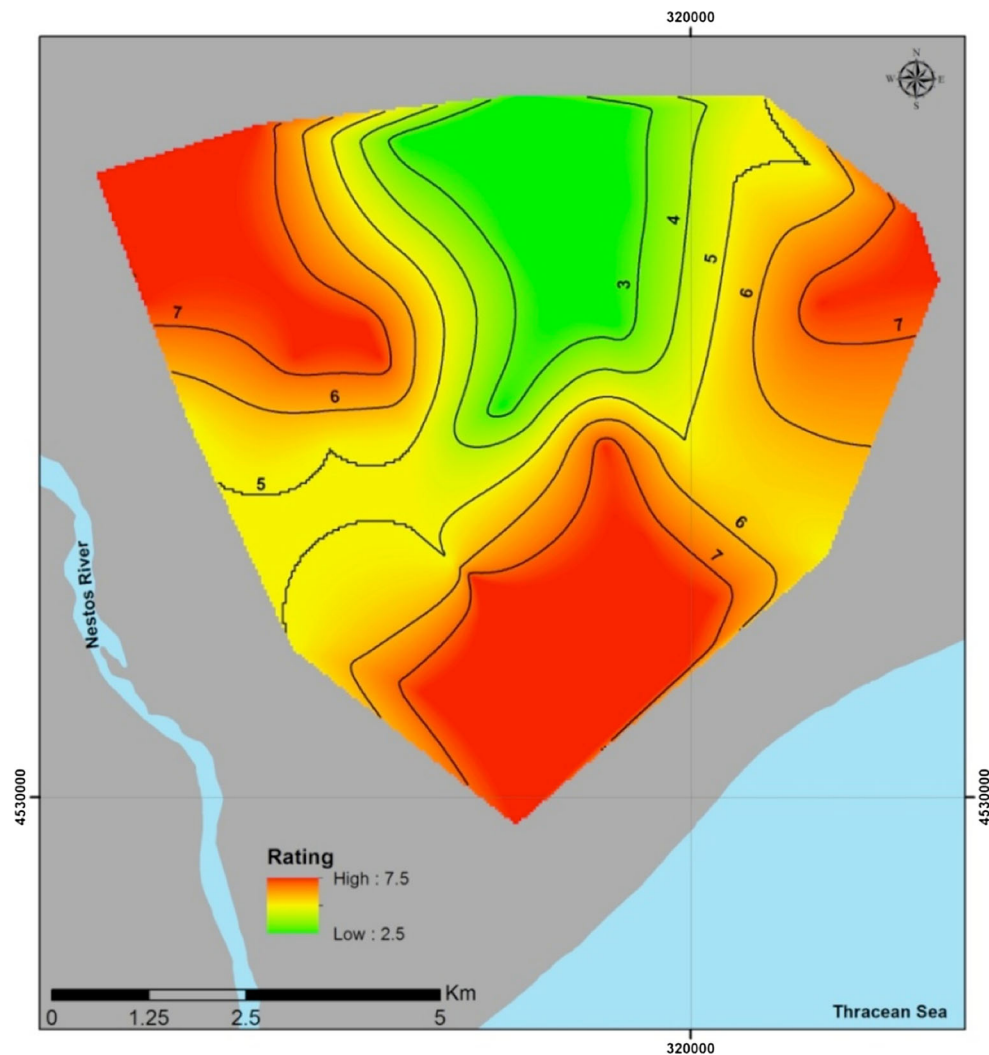
Table 13 Ranges and ratings for height of groundwater level above sea level (Chachadi 2005)

Range	Rating
Height of groundwater level above sea level (L)	
<1.0	10
1.0–1.5	7.5
1.5–2.0	5
>2.0	2.5

area were utilized to assess the impact level of existing seawater intrusion, as chloride ions are considered conservative ions (i.e., do not participate on ion exchange processes), hence can be seen as a safe indicator of seawater intrusion.

A value of chloride concentration was assigned for each observation well, and then they were classified according to

GALDIT rating values, from 2.5 to 10 for minimum and maximum vulnerability impact, respectively (Table 15). The ranges and ratings were re-adjusted to the chloride concentrations, since the parameter for impact of existing status of seawater intrusion is characterized by Revelle coefficient values in the original GALDIT methodology.

**Fig. 13** Categorization of hydraulic conductivity parameter after GALDIT rating values

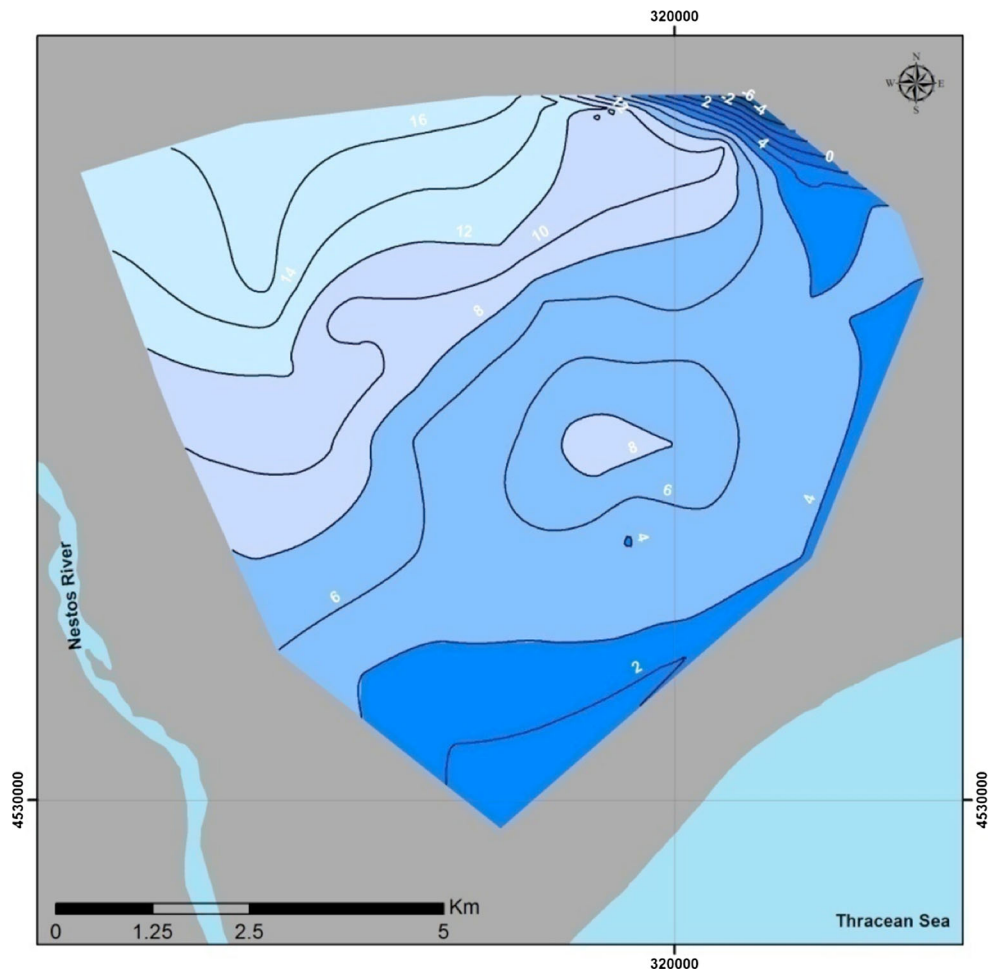


Fig. 14 Height of groundwater elevation above sea level distribution map (April 2009)

The map displayed in the Fig. 21 exhibits the highest chloride concentration at east/southeast part of the study area, where the values range from 200 mg/L to above 500 mg/L and, therefore, with ratings from 5 to 10 (Fig. 22). It is worth mentioning that chloride concentration is much lower in the south-western part of the study area even though it is closer to the coast due to the recharging conditions from R. Nestos along the NW–SW boundaries of the investigated aquifer.

Thickness of the aquifer (*T*)

In unconfined aquifers, this parameter plays an important role in determining the extent and magnitude of seawater intrusion in coastal areas (Chachadi 2005). According to Pliakas et al. (2001), the shallow aquifer system extends down to a depth of approximately 30 m. Additionally, the average of 3-m depth was found for the water table in this

phreatic system and, thus, the saturated thickness of 27 m was used for all observation wells. It means that the whole area falls under rating 10 (highest vulnerability impact), as the aquifer thickness exceeds the 10 m proposed by GALDIT model (Table 16).

GALDIT groundwater vulnerability index

The groundwater vulnerability map shown in Fig. 23 illustrates the conditions of the research area concerning the risk of seawater intrusion, according to GALDIT model. The GALDIT vulnerability index (GVI) distribution map indicates two areas at the northeastern and southern part with values above 7.5, denoting high vulnerability and corresponding to approximately 45 % of the entire area. The rest of the area (55 %) shows values ranging from 5 to 7.5, which refers to moderate vulnerability.

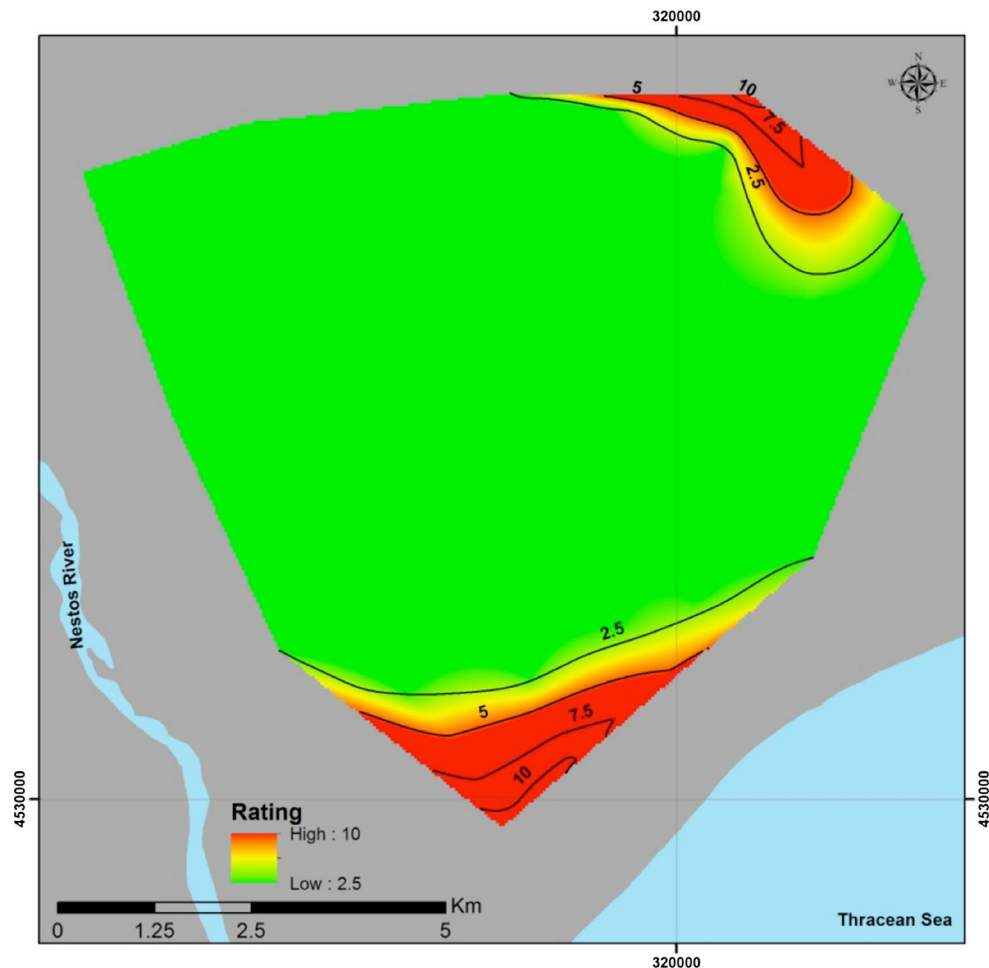


Fig. 15 Categorization of height of groundwater Level above sea level parameter after GALDIT rating values (April 2009)

The overpumping of coastal wells by farmers to meet agricultural demands causes lowering of groundwater table in the two regions, at northeastern and southern. It can be seen in Fig. 15, where the parameter height of groundwater level above sea level (L) depicts these two critical areas with low values, even negative values of groundwater table. Additionally, the distance from the shoreline parameter (D) shows high vulnerability for all the eastern part of the area, including the south and northeast regions (Fig. 20).

Laspas Stream could be also considered a source of chloride contamination, as it receives irrigation return flow from northern, which might contain chloride ions.

Conclusions

The shallow aquifer system in the study area provides fresh water mainly for irrigation purposes, since the area is highly cultivated. These intensive agricultural activities are responsible for a large amount of fertilizers and pesticides introduced into subsurface, contaminating soils and groundwater. Furthermore, livestock, stables and piggeries also contribute to nitrate pollution. Due to the agricultural development within the eastern delta of Nestos River, a large number of coastal wells are pumped to meet the irrigation needs. This means of exploitation of the aquifer system causes another type of contamination, known as seawater intrusion.

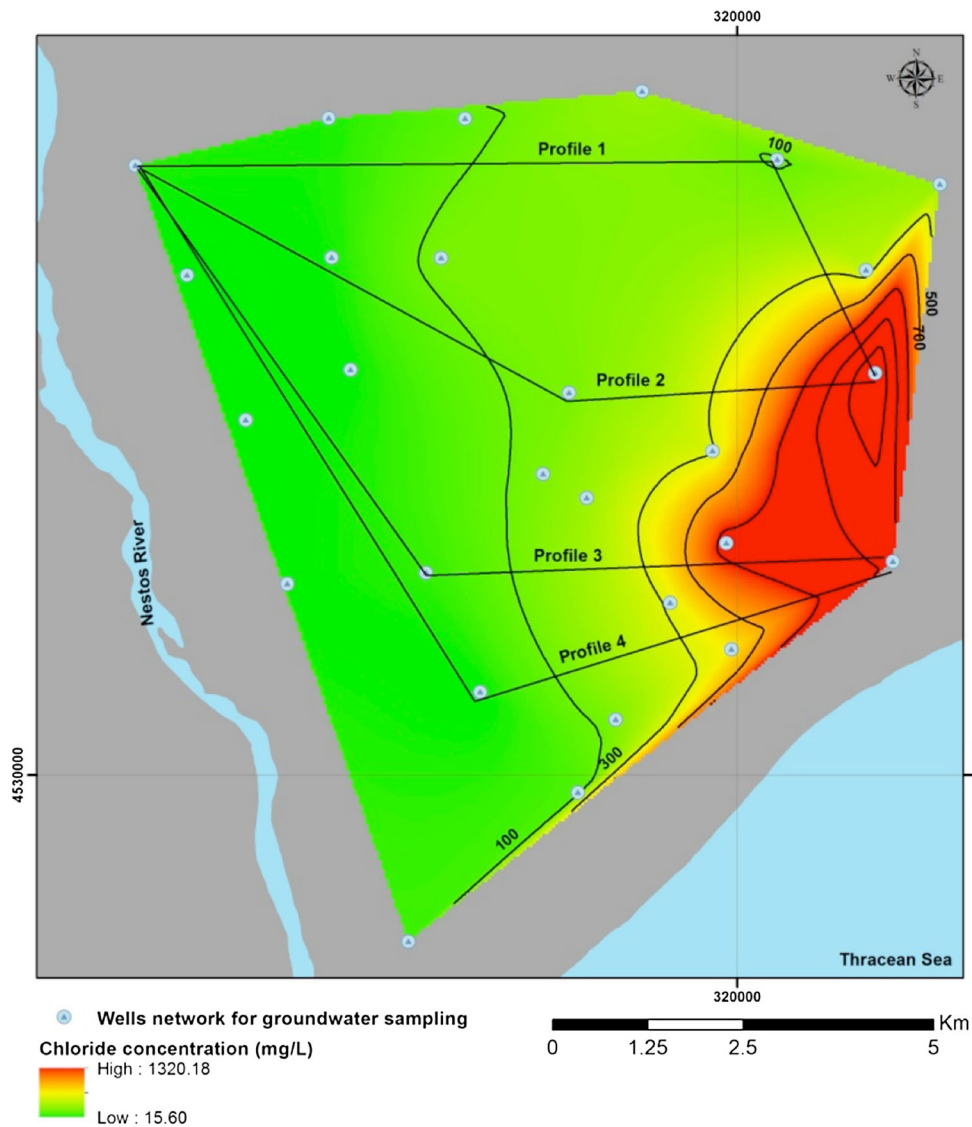


Fig. 16 Location of the profiles 1–4 and chloride concentration distribution in groundwater (July 2009)

Considering the great concern about water resources involving researchers, authorities, decision makers and stakeholders, methodologies were developed to evaluate the potential risk to contamination of a given area. In the case of eastern part of Nestos River, two groundwater vulnerability indices were applied, namely: DRASTIC—assessing the groundwater vulnerability to pollution considering a source on ground surface; and GALDIT—evaluating the groundwater vulnerability to seawater intrusion in coastal regions.

The final DRASTIC vulnerability index distribution map presents values ranging from 90 to 130 at the northern and northeastern part of the study area, corresponding to approximately 40 % of the entire area. These values are considered as low vulnerability indices' values. The values are higher towards the south and northwest, reaching 150, equivalent to approximately 60 % of the area and corresponding to moderate vulnerability indices values.

The pesticide version of DRASTIC depicts higher values than the original version. The northern and northeastern

regions show values ranging from 115 to 170, meaning moderate to high vulnerability. This range encompasses approximately 40 % of the study area. Towards the

northwest, eastern and south, values ranging from 170 to 190 are found, corresponding to 60 % of the entire area. These regions fall under high vulnerability.

It is evident the change from low/moderate vulnerability in the original version to moderate/high vulnerability in the pesticides version. This makes clear that the parameters soil media, topography, impact of the vadose zone and hydraulic conductivity play an important role in determining the vulnerability of an area subject to intensive agricultural practices.

Laspías Stream is a canal located at east/northeast of the study area, receiving treated sewage effluents, industrial wastes and irrigation waters from the north. Although this canal is present at northeastern of the study area, the vulnerability values are not high in such area, classified as low vulnerability in the DRASTIC original version. It can be related to the depth to water table (April 2009), which is deeper at north/northeast part of the study area due to higher topographical elevation.

Furthermore, this area is the subject of extensive groundwater pumping and, consequently, lowering of groundwater table. The deeper the water table within the

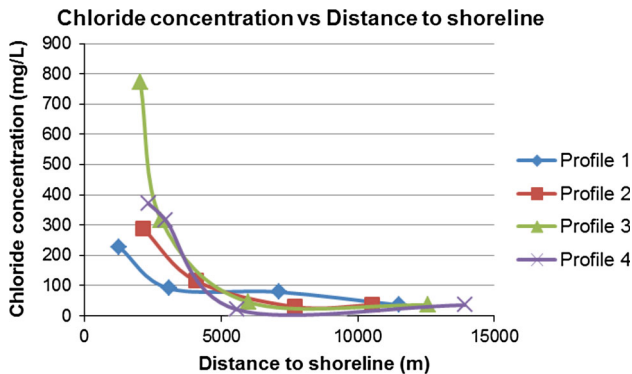


Fig. 17 Profiles 1–4, identifying relation between chloride concentrations and distance to shoreline

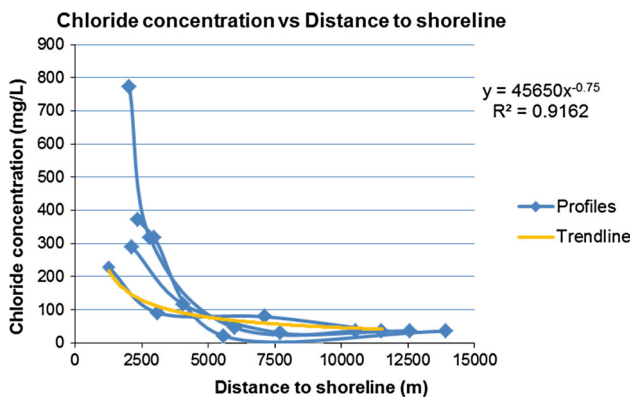


Fig. 18 Regression analysis and trendline for the chloride concentration and shoreline distance relation

Table 14 Modified range values for the parameter of distance from the shoreline of GALDIT model

Range	Rating
Distance from the shoreline (<i>D</i>)	
<2,500	10
2,500–5,000	7.5
5,000–7,500	5
>7,500	2.5

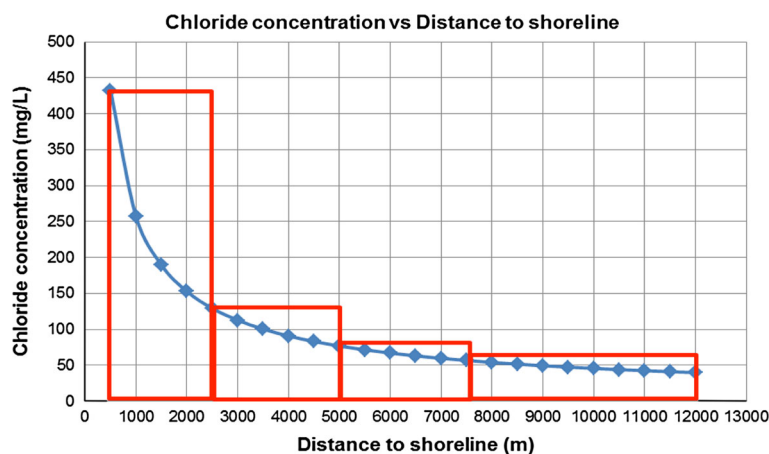


Fig. 19 Intervals defined through the curve of the regression equation

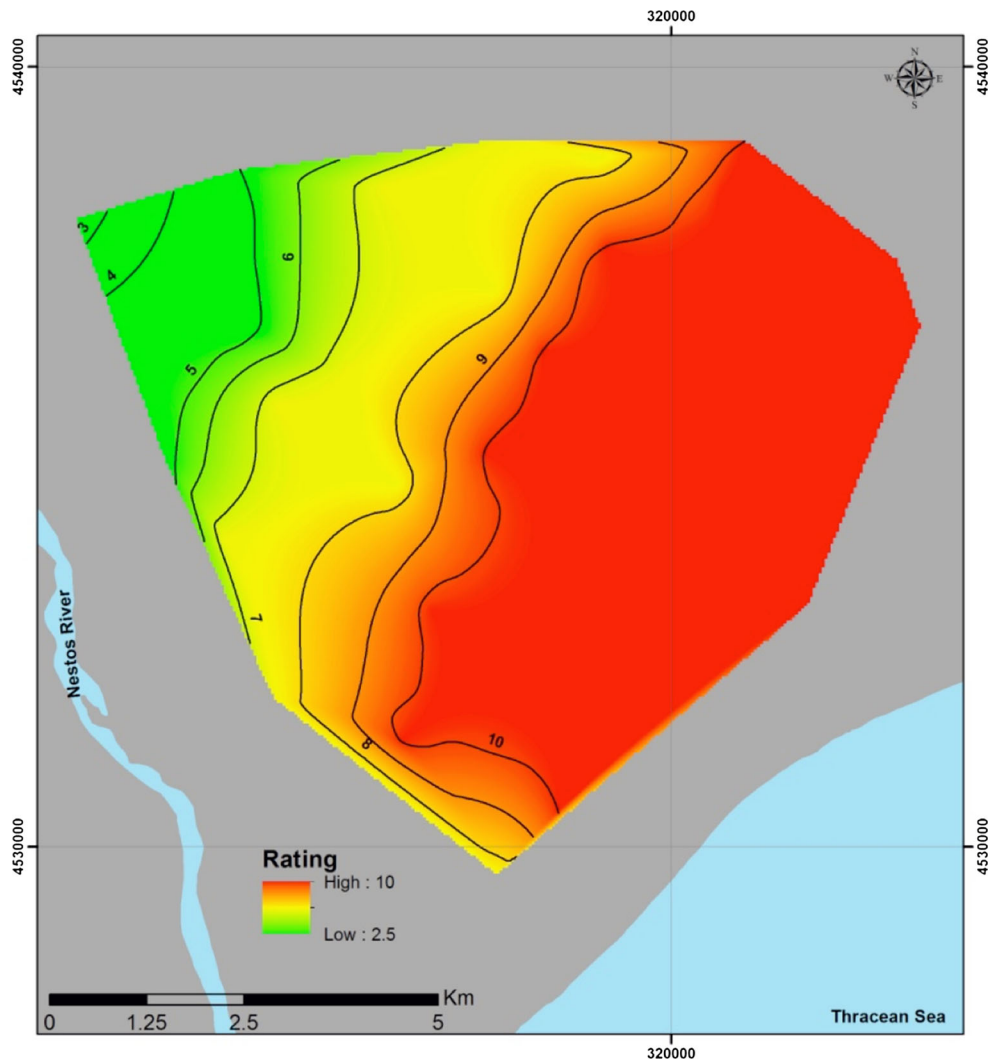


Fig. 20 Categorization of distance from the shoreline parameter after GALDIT modified rating values

Table 15 Ranges and ratings for impact of existing status of seawater intrusion

Range	Rating
Impact of existing status of seawater intrusion Cl^- (mg/L)	
>500	10
250–500	7.5
100–250	5
<100	2.5

region, the longer is the downward movement of the contaminant before it reaches the groundwater and, consequently, a lower vulnerability in this area. It constitutes strong evidence of how important is the depth to water table parameter for DRASTIC model.

It is still observed in both versions of DRASTIC that the values are higher towards the east, where the groundwater table is shallower, and the vulnerability is totally related to Laspas Stream, which is the main source of pollution in the eastern boundary of the study area.

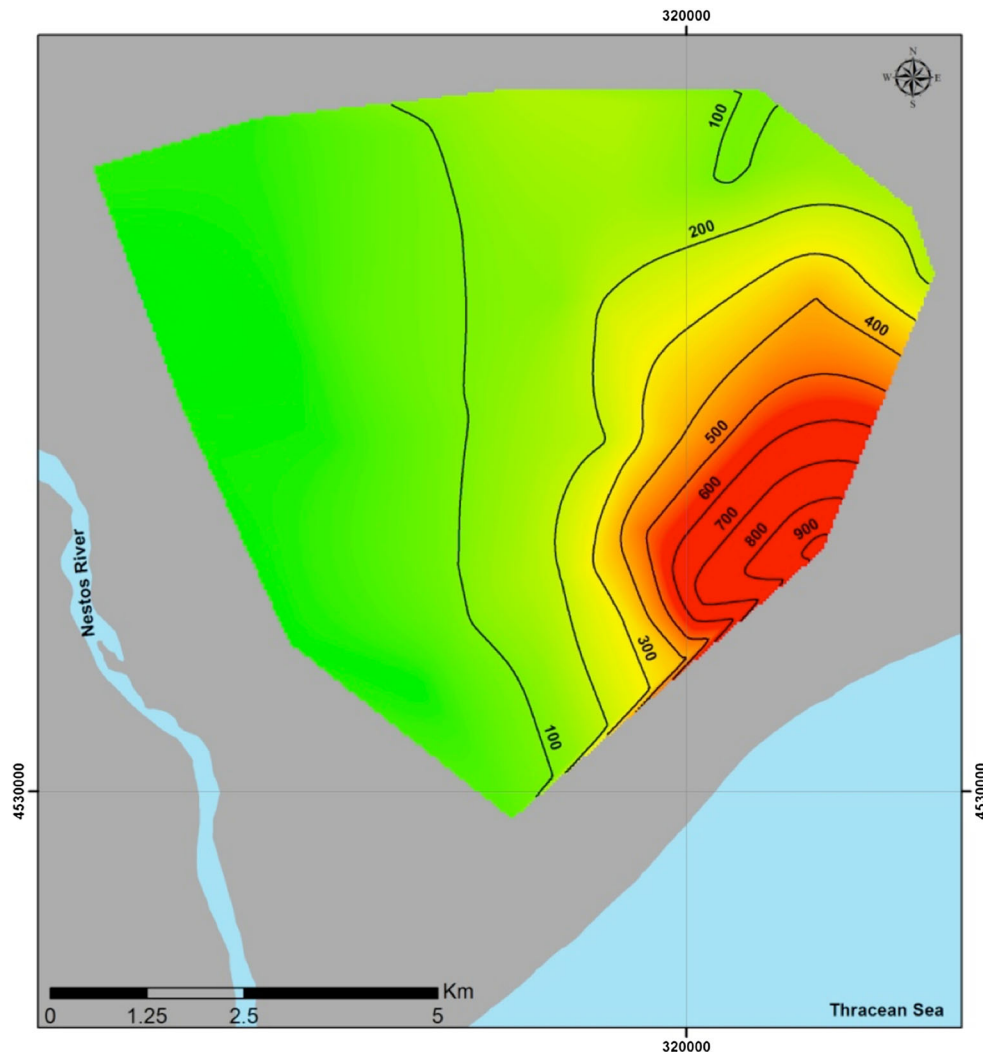


Fig. 21 Chloride concentration distribution map (mg/L) (July 2009)

The nitrate distribution map in groundwater corroborates the idea of nitrate contamination by point sources pollution (PSP), since the area has a significant number of stables and piggeries, besides the use of fertilizers in the crops. From Fig. 24, it is observed that the PSP are distributed in the entire area, increasing the values towards northwest and south. The shallow groundwater table at northwestern makes the vulnerability higher in that region, once again proving the high importance of this parameter for DRASTIC model.

DRASTIC vulnerability index assessment shows that the depth to water table is the most important parameter in the case of eastern delta of Nestos River, since it affects directly the vulnerability of the aquifer in regions with shallower or deeper water tables, in both versions: original and pesticides one.

Additionally, the parameters soil media, topography, impact of the vadose zone and hydraulic conductivity are significant in determining the vulnerability of an area subject to intensive agricultural practices. It can be seen in DRASTIC pesticide version, where the change in these parameters raised the vulnerability conditions of the research area.

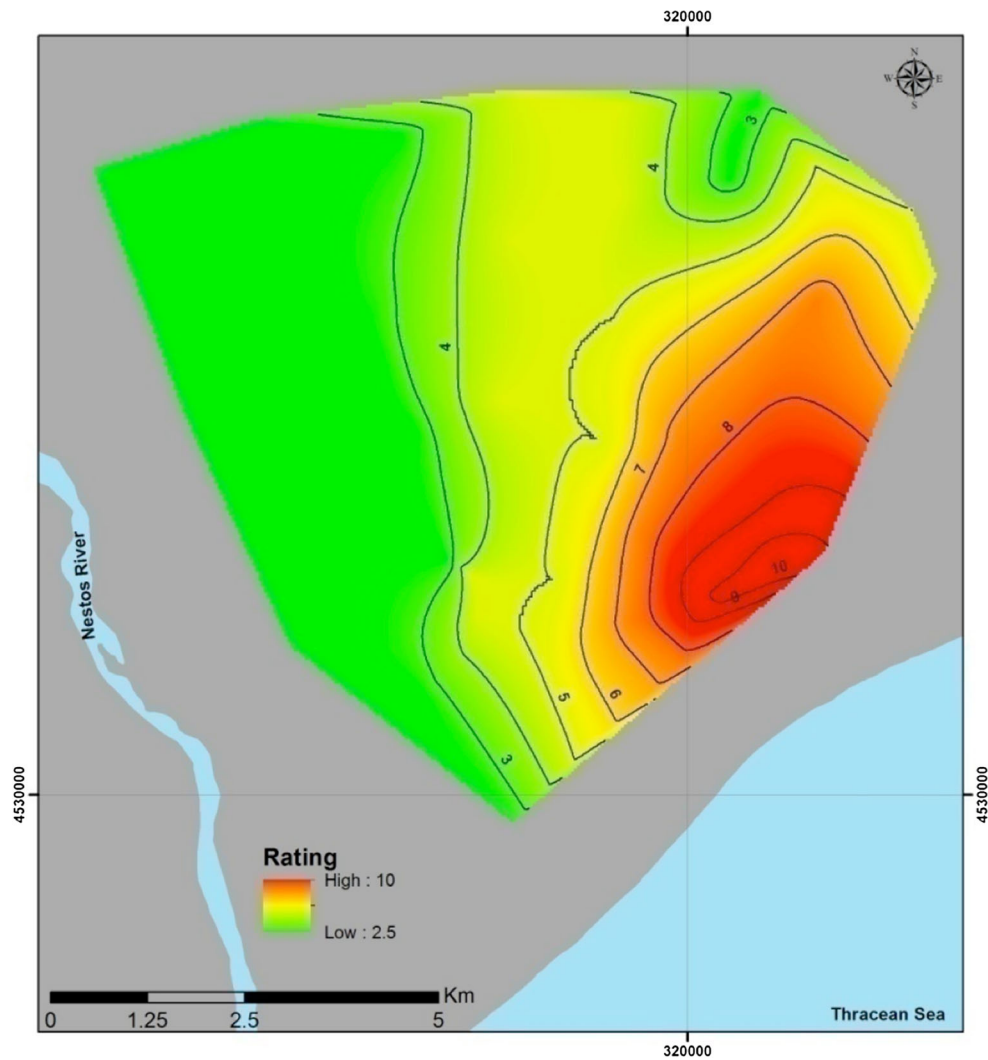


Fig. 22 Categorization of chloride concentration parameter after GALDIT (July 2009)

The main sources of nitrate pollution in the study area are point sources pollution (PSP) as stables and piggeries, fertilizers and the Laspia Stream located at east.

The GALDIT vulnerability index (GVI) distribution map indicates two areas at the northeastern and southern part with values above 7.5, denoting high vulnerability and corresponding to approximately 45 % of the entire area. The rest of the area (55 %) shows values ranging from 5 to 7.5, which means moderate vulnerability.

The overexploitation of coastal wells causes lowering of groundwater table in these two critical regions. It can be seen in the height of groundwater level parameter map, which displays the groundwater elevation a.m.s.l. distribution in the study area in April 2009, prior to the irrigation period. It means that even in normal conditions, i.e., considering the natural recharge in the wet season, there has been a severe decline of groundwater levels in that region.

Table 16 Ranges and ratings for thickness of the aquifer being mapped (Chachadi 2005)

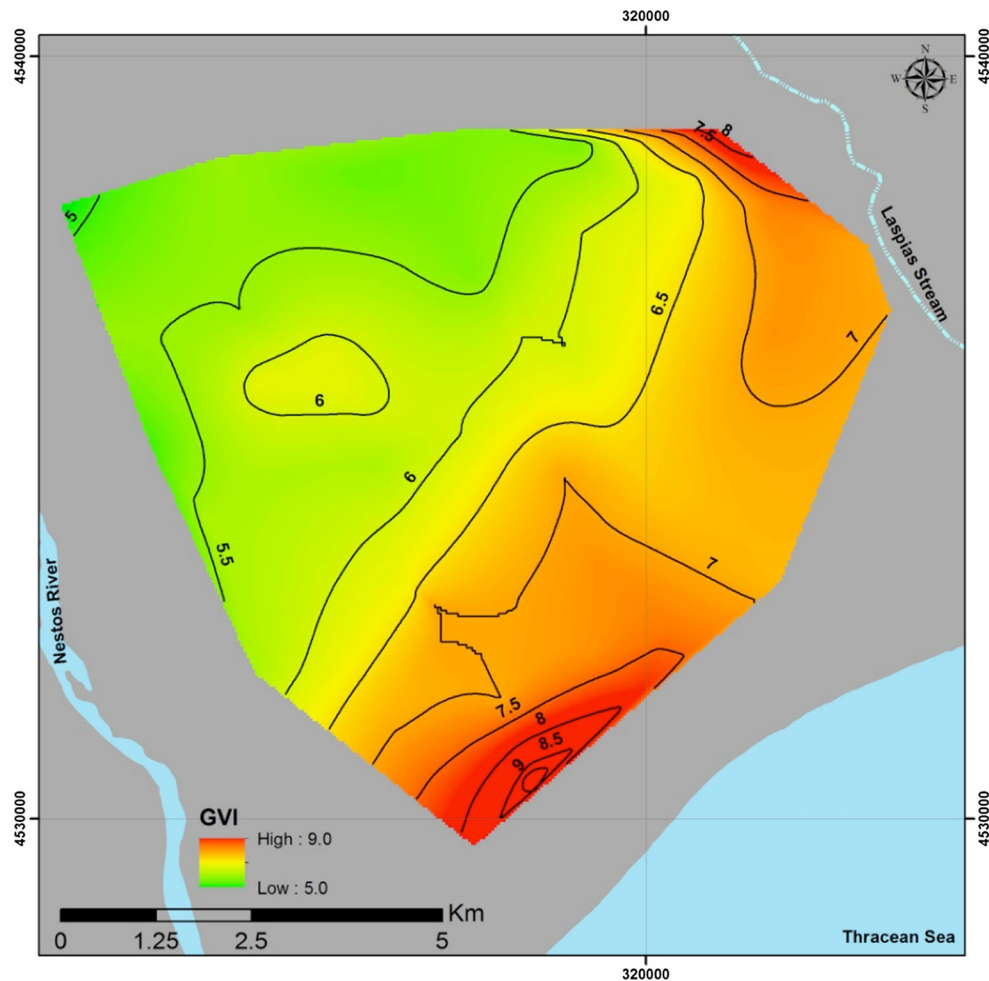
Range	Rating
Thickness of the aquifer being mapped (m)	
>10	10
7.5–10	7.5
5–7.5	5
<5	2.5

The chloride distribution map in groundwater shows that the seawater front has moved towards inland, with the highest values of chloride at east/southeast of the study area. It makes the distance from shoreline parameter a significant factor for determining the vulnerability of the

aquifer, since the area with high-chloride concentration was considered the seawater front.

The Laspias Stream, located at east/northeast of the study area, receives irrigation return flow from northern, which might contain chloride ions. The chloride ion infiltrates on superficial soil, becoming a threat to the crops and migrating through the vadose zone downwards until reaching the groundwater table.

GALDIT vulnerability index demonstrates that the parameter height of groundwater level above sea level is a very significant factor for evaluating the vulnerability of the study area to seawater intrusion. Its importance can be proved by the fact that the two more vulnerable areas (at northeast and south) are the areas of lowest groundwater levels (Fig. 23).

**Fig. 23** GALDIT groundwater vulnerability index (GVI) distribution map (July 2009)

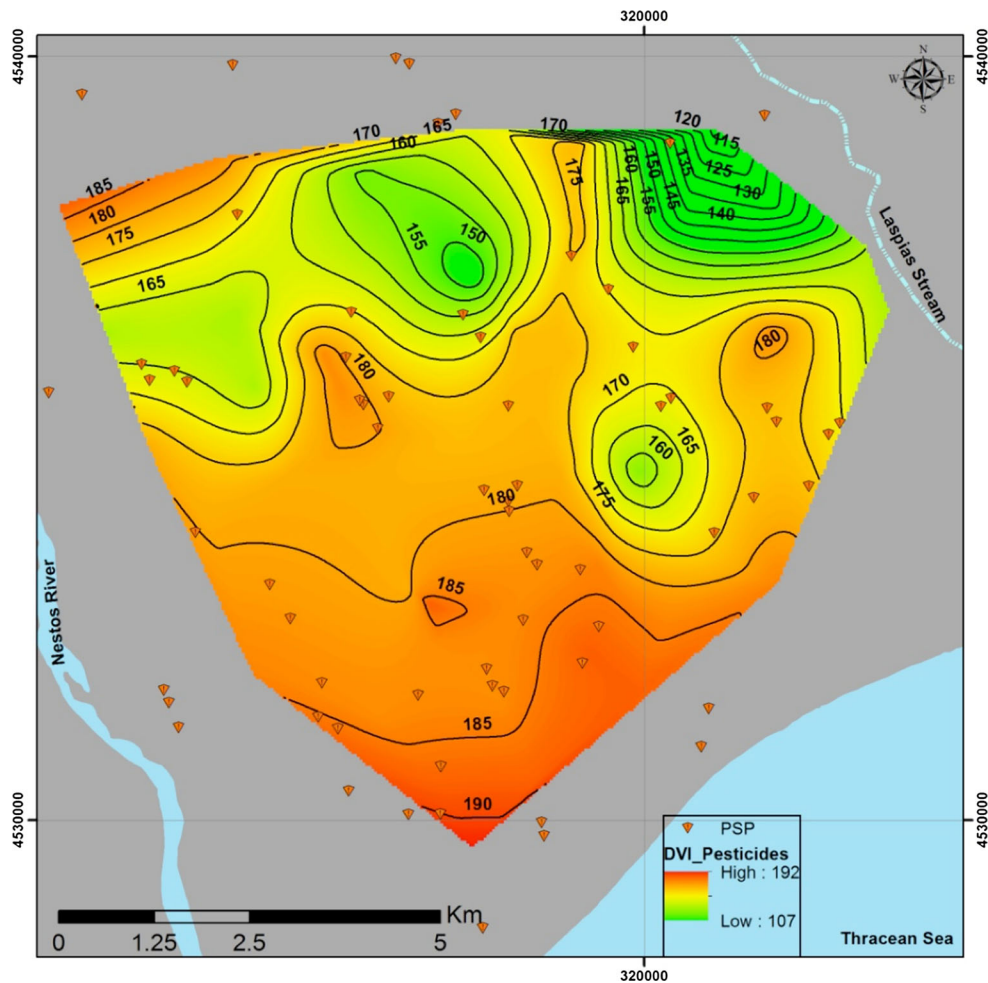


Fig. 24 DRASTIC (pesticides) groundwater vulnerability index (DVI) distribution map with PSP (point sources pollution) (July 2009)

Additionally, the distance from shoreline and impact of existing status of seawater intrusion parameters show the migration of seawater front towards the mainland, which has been caused by the extensive pumping of coastal wells for agricultural purposes.

Two different sources of chloride contamination are detected in the research area: seawater intrusion due to overexploitation of the coastal aquifer, and Laspis Stream located at east/northeast of the study area.

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