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Updated groundwater vulnerability evaluation at a coastal aquifer system in NE Greece

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Abstract: This paper presents the updated vulnerability assessment of Xilagani - Imeros aquifer system in the coastal plain region of Rhodope Prefecture, NE Greece, in the framework of the groundwater management in the region. Information regarding the geological and geomorphological environment, as well as data concerning the hydrologic and hydrogeological regime of the study area are stated. The paper presents the application of DRASTIC and GALDIT vulnerability indexes procedures and the design of easy to use vulnerability maps in order to identify the parts where there is a serious potential for groundwater resources qualitative degradation due to agricultural pollution (DRASTIC approach) or seawater intrusion (GALDIT approach). The research is based on the results of hydrogeological studies in the study area for the year 2015 compared to the year 2006, including field hydrogeological measurements and chemical analyses in the laboratory, as well as the design of groundwater piezometric maps and hydrochemical maps. It is worth mentioning that DRASTIC index values for the year 2015 do not differ substantially compared to the corresponding values for the year 2006. Instead, increase of GALDIT index values is recorded for the year 2015 indicating worsening of the groundwater salinization status due to seawater intrusion.

Key words: DRASTIC GALDIT Vulnerability index, Coastal hydrogeology, Groundwater pollution, Seawater intrusion, Coastal aquifer management

1. INTRODUCTION

This paper refers to the assessment of the updated groundwater vulnerability of the Xilagani – Imeros coastal aquifer system, at the SW part of Rhodope Prefecture, NE Greece. The research is based on the results of previous hydrogeological studies in the study area (Sakkas et al., 1998; Pliakas et al., 2001, 2004, 2007). The paper presents the application of DRASTIC and GALDIT vulnerability indexes procedures and the design of easy to use vulnerability maps in order to identify the parts where there is a serious potential for groundwater resources qualitative degradation due to agricultural pollution (DRASTIC approach) or seawater intrusion (GALDIT approach) for the year 2015 compared to the year 2006.

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). Pedreira et al. (2015) mention that 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.

Recinos et al. (2015) note that Chachadi and Lobo Ferreira (2001) realized the necessity for developing a numerical ranking system to assess the general seawater intrusion potential of each hydrogeological setting. GALDIT vulnerability index (Lobo Ferreira et al., 2005; Chachadi and Lobo-Ferreira, 2005) involves measurable parameters which can be synthesized to provide an efficient tool for mapping the seawater intrusion potential of a coastal aquifer. Once the GALDIT index has been computed, it is possible to identify areas that are more likely to be susceptible to seawater intrusion than other areas. The higher the vulnerability index, the greater the seawater intrusion potential. Pedreira et al. (2015) point out that 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.

2. DESCRIPTION OF THE STUDY AREA

The plain area of Xilagani – Imeros has mild morphologic characteristics with low elevation, extended between Lissos River and the western foot of Ismaros Mount, whereas Thracian Sea covers the southern boundaries of the area (Figure 1). The geological environment of the study area includes recent sediments originated from Lissos River -and some other branches of the same river- overlying Neogene deposits or Paleogene deposits of Rhodope massif (Pliakas et al., 2004).

The main cultivation type of the area is cotton, while the southern part of the area of investigation is not arable due to groundwater salinization. There are 55 groundwater wells (about 10 of them abandoned), with mean depth of 70 m and mean pumping rate of approximately 40 m^3/h, while at the northern parts of the site the groundwater wells present pumping rates of approximately 60 to 70 m^3/h (Pliakas et al., 2004, 2007).

According to Kallioras et al. (2011), the aquifer system of the study area contains clay materials and appears in the form of successive layers composed of clay-sands and sands with a width ranging from 1 to 10 m, with many interferences of clay layers. Relevant hydrogeological studies of the semi-confined aquifer of the study area (Sakkas et al., 1998; Pliakas et al., 2001, 2004, 2007) have shown 4 distinct main geoelectrical formations categorized according to the values of their specific electrical resistivity, as follows (ASCE, 1987; Kallergis, 2000): coarse grained sand (>40 Ohm×m), fine grained sand (25-40 Ohm×m), clay-sand materials (15-25 Ohm×m), clay (<15 Ohm×m), while the dominance of clay and clay-sand materials throughout the whole extent of the study site is very distinct (the positions of the relevant geoelectric sounding measurements and their section axes are shown in Figure 1 upper). According to these studies, the groundwater level gradually increases from October to March, due to natural recharge from direct infiltration from precipitation (at parts of the aquifer where it appears semi-confined or unconfined), percolation from Lissos River and lateral inflows from the NE part of the study area where there is a hydraulic connection with the mountainous zone (Figure 1, lower). During the period between April and October the groundwater level appears below the mean sea level fact which is attributed to the overpumping conditions for irrigation purposes.

The evaluation and assessment of the qualitative characteristics of the study aquifer involved the determination of certain chemical parameters, such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, PO_4^{3}, NO_3^-, NO_2^-, and certain physicochemical parameters such as alkalinity P, alkalinity M, total hardness and pH (July 2015). The majority of the groundwater samples of the investigated aquifer (Figure 1 upper), according to specific standards and drinking water limits (Government Gazette-GG 630, 26-4-2007, GG 2075, 25-9-2009, GG 3322, 30-12-2011; Kallergis, 2000), are characterized as non-potable, as the concentrations of Cl^- (163-1,400 mg/L), Na^+ (175-680 mg/L), K^+ (5-27 mg/L), Ca^{2+} (32-497 mg/L), Mg^{2+} (16-256 mg/L) are above the quality standards. The values of electrical conductivity range between 1,133-4,750 μS/cm, where the higher values of electrical conductivity appear within the southern (coastal) part of the study site, fact which imposes the argument of seawater intrusion conditions.

3. APPLICATION OF DRASTIC AND GALDIT METHODS

DRASTIC has been the most commonly used for mapping aquifer vulnerability in porous aquifers (Aller et al., 1987). The DRASTIC method considers seven parameters, which taken together, provide the acronym (Panagopoulos et al., 2006; Sener et al., 2009). These are depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), influence of the vadose zone (I) and hydraulic conductivity (C). Each parameter is subdivided into ranges and is assigned different ratings in a scale of 1 (least contamination potential) to 10 (highest contamination potential). This rating is scaled by a pesticide and DRASTIC weighting factors ranging between 1 (least significant) and 5 (most significant).

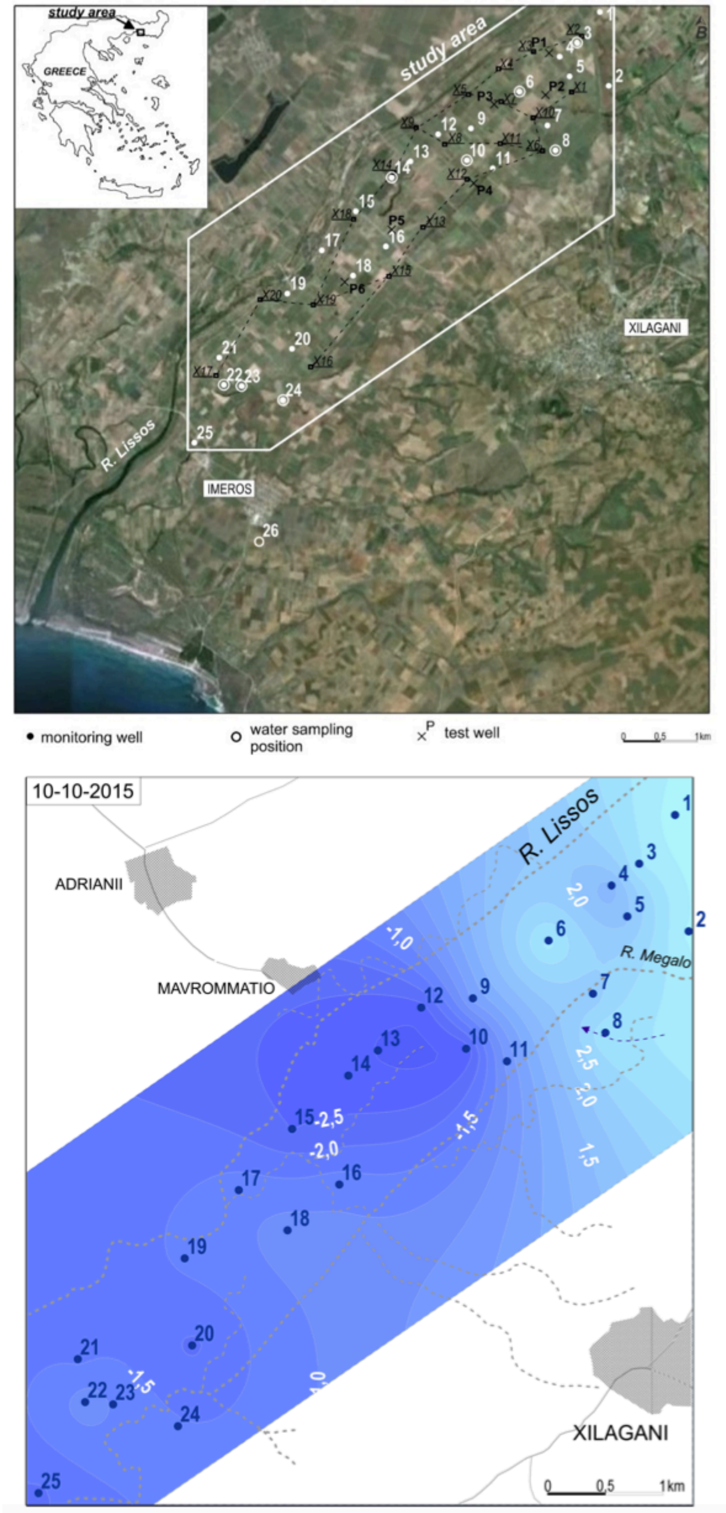

Figure 1. Upper: Study area, positions of monitoring wells, test wells and geoelectric sounding measurements and their section axes (Kallioras et al., 2011). Lower: Piezometric map (m a.s.l.) (10-10-2015) (dotted line: main groundwater recharge axis).

The linear additive combination of the above parameters with the ratings and weights was used to calculate the DRASTIC Vulnerability Index (DVI) as given below (Aller et al., 1987; Sener et al., 2009):

$$DVI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad (1)$$

where r is the rating for corresponding ranges and w the weight for each parameter.

The calculation of Pesticide DVI (considering S, T, I, C parameters with different weights compared to the original DRASTIC method) included the values of all parameters in every single investigated groundwater well (Table 1). The results from the application of DRASTIC vulnerability index have been linked with GIS, for the design of a vulnerability map (DVI – 2015) in order to identify the parts where there is a serious potential for groundwater resources qualitative degradation (Figure 2, upper - left). Additionally, nitrate distribution map has been designed (nitrate ions in mg/L, July 2015) (Figure 2, upper - middle), where it is revealed that the NE part of the study area where increased nitrate concentrations are present coincides with the areas of high vulnerability based on the application of DVI (DVI >160).

Pesticide DVI values range from 119 to 183 in 2006, while from 115 to 179 in 2015 (Table 1). In both approaches, DVI values are higher in the northern parts of the study area, and gradually decrease towards the southern parts. In 2015, there is an upward trend in the southern wells (Figure 2, upper - left, Figure 2, upper - right).

The development of GALDIT index (GVI) is aiming the assessment of aquifer vulnerability to sea-water intrusion in coastal aquifers (Lobo Ferreira et al., 2005). The most important factors controlling seawater intrusion were found to be the following: Groundwater occurrence (aquifer type; unconfined, confined and leaky confined); Aquifer hydraulic conductivity; Depth to groundwater Level above the sea; Distance from the shore (distance inland perpendicular from shoreline); Impact of existing status of sea water intrusion in the area; and Thickness of the aquifer, which is being mapped. The acronym GALDIT is formed from the highlighted letters of the previous parameters. According to Kallioras et al. (2011), these factors, in combination, are determined to include the basic requirements needed to assess the general seawater intrusion potential of each hydrogeological setting. A numerical ranking system to assess seawater intrusion potential in hydrogeological settings has been devised using GALDIT factors. The system contains three significant parts: weights, ranges, and ratings. Each GALDIT factor has been evaluated with respect to the other to determine the relative importance of each factor. Each of the six indicators has a pre-determined fixed weight that reflects its relative importance to seawater intrusion. The GALDIT Index is then obtained by computing the individual indicator scores and summing them as per the following expression:

$$GVI = \sum_{i=1}^{6}\{(W_i)R_i\} / \sum_{i=1}^{6} W_i \quad (2)$$

where Wi is the weight of the i^{th} indicator and Ri is the importance rating of the i^{th} indicator.

Once the GALDIT-Index has been computed, it is therefore possible to classify the coastal GALDIT Vulnerability Index, GVI, was calculated according to the values of each parameter in every single groundwater well (Table 1). The results from the application of GALDIT vulnerability index were linked with GIS in order to design vulnerability maps for the study area with respect to the potential for aquifer contamination due to seawater intrusion (Figure 2, lower – left; GVI - 2015). Revelle coefficient was also calculated and distributed throughout the entire study area, so that the Revelle distribution map (July 2015) is correlated against the vulnerability map from the application of GALDIT VI (Figure 2, lower - middle). It was concluded that at the SW part of the study area (with a direction towards the shoreline) there is a coincidence between the zone of high vulnerability based of GALDIT VI (GVI > 7.5) and the high Revelle coefficient.

Low GVI values are observed in 2015 at the NE part of the study area, which become moderate at the area of the wells 6, 7, 8, as in 2006, with significant increase especially south of the area of the wells 15 and 16. GVI values have increased from 2006 to 2015, in 2006 ranging from 4.5 to 8.5 with an average value of 6.9, while in 2015 from 4.5 to 9 with an average value of 7.1 (Figure 2, lower – left; Figure 2, lower - right).

Table 1. [A]: DRASTIC Vulnerability Index (DVI) rating and weighting values for the various hydrogeological parameter settings. [B]: GALDIT Vulnerability Index (GVI) rating and weighting values for the various hydrogeological parameter settings (10-10-2015).

[A]: 2015 – Pesticide DVI: 115-179						
D (m) [1]	R (mm) [2]	A	S	T (%)	I	C (m/s)
2.2-8.4	32.9-41.1	clay - sandy deposits	clay - sandy material	0.1-1.2	clay - sandy deposits	1×10^{-6}-1×10^{-4}
Dr	Rr	Ar	Sr	Tr	Ir	Cr
4-10	1-2	6-9	4-6	9-10	4-9	2.5-7.5
Dw	Rw	Aw	Sw	Tw	Iw	Cw
5	4	3	5	3	3	2
	Vulnerability:	Very high	High	Moderate	Low	Very low
	DVI:	>160	140-160	120-140	100-120	<100

[B]: 2015 – GVI: 4.5-9.0					
G	A (m/s)	L (m) [3]	D (m)	I (Revelle) [4]	T (m)
semi-confined aquifer	1×10^{-6}-1×10^{-4}	-3.2-3.7	3263-10790	0.7-10.9	7-27
R1	R2	R3	R4	R5	R6
10	2.5-7.5	2.5-10	2.5-10	2.5-10	7.5-10
W1	W2	W3	W4	W5	W6
1	3	4	4	1	2
		Vulnerability:	High	Moderate	Low
		GVI:	≥ 7.5	5 – 7.5	< 5

[1]: 10-10-2015, [2]: infiltration: 10% of mean annual rainfall (Kallioras et al., 2010) (2011-2014: 411.9 mm), [3]: 10-10-2015, [4]: July 2015

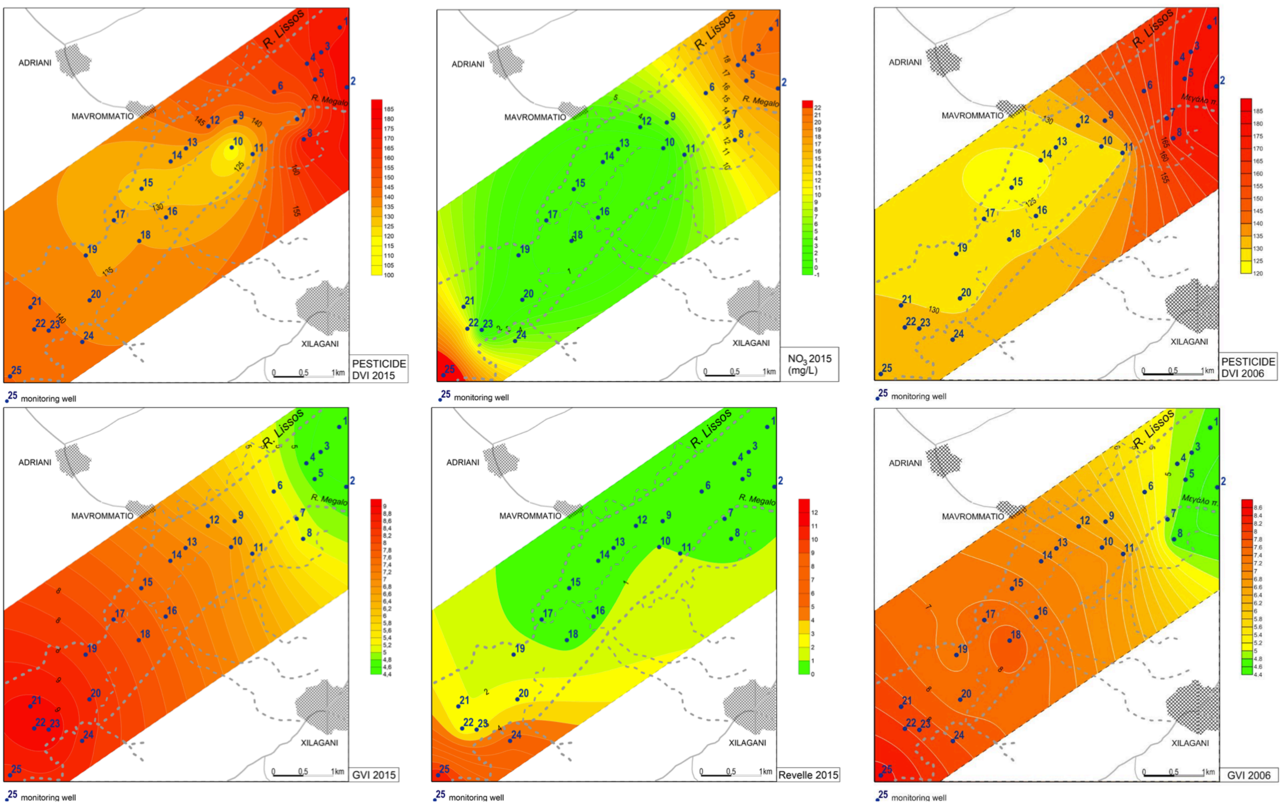

Figure 2. Upper left: Pesticide DRASTIC aquifer vulnerability map (DVI values) (2015). Upper middle: distribution of nitrates (NO_3^-) concentrations map (2015). Upper right: Pesticide DRASTIC aquifer vulnerability map (DVI values) (2006, Kallioras et al., 2011). Lower left: GALDIT aquifer vulnerability map (2015). Lower middle: Distribution of Revelle values map (2015). Lower right GALDIT aquifer vulnerability map (2006, Kallioras et al., 2011).

4. CONCLUSIONS

The updated vulnerability assessment of Xilagani - Imeros aquifer system in the coastal plain region of Rhodope Prefecture, NE Greece, is presented in this paper. The research included the analysis and interpretation of DRASTIC and GALDIT vulnerability indexes spatial distribution with respect to the spatial distribution of nitrate concentration and Revelle coefficient values, respectively, for the year 2015. It is worth mentioning that DRASTIC index values for the year 2015 do not differ substantially compared to the corresponding values for the year 2006. Instead, increase of GALDIT index values is recorded for the year 2015 indicating worsening of the groundwater salinization status due to seawater intrusion.

Margane (2003) states that DRASTIC method is a popular approach to groundwater vulnerability assessments because it is relatively inexpensive, straightforward, and uses data that are commonly available or estimated and produces an end product that is easily interpreted and incorporated into the decision-making process. On the other hand, Pedreira et al. (2015) mention that GALDIT index is a relative tool and it does not exclude the need for more detailed field investigations.

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