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A Modified GALDIT Method to Assess Groundwater Vulnerability to Salinization—Application to Rhodope Coastal Aquifer (North Greece)

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Abstract: Aquifer overexploitation in coastal aquifers has led to seawater intrusion that causes severe salinization effects on the groundwater system. The most widespread method for assessing groundwater vulnerability to seawater intrusion, the dominant cause of salinization in coastal aquifers, is the GALDIT method, with numerous applications globally. The present study proposes a modified version of the GALDIT method (GALDIT-I) to evaluate the vulnerability of salinization, including its potential additional sources. Both methods have been applied to Rhodope coastal aquifer, an intensively cultivated agricultural area subject to multiple salinization sources. The basic modifications of the proposed GALDIT-I method include different weighting factors and modification of classes for critical parameters, the use of a different indicator (TDS) for the estimation of the Impact factor and, overall, the address of the concept of groundwater salinization instead of seawater intrusion only. The differences in the results of the two methods were significant, as the modified version exhibited a more finite and realistic vulnerability capture, according to the area's existing hydrogeological and hydrogeochemical knowledge. The original GALDIT method showed an area of nearly 80% as medium vulnerable with very limited spatial deviations. On the other hand, the proposed modified GALDIT method depicted high vulnerability hotspots away from the shoreline, indicating various salinity sources. The validation of the modified method showed that nearly 80% of the sampling points present very good to perfect match between the salinity assessment and the concentration of Cl^-, indicating the successful validation of the method. Overall, the GALDIT-I method facilitated groundwater vulnerability assessment to salinization more accurately and exhibited a more discrete spatial assessment, thus, it could be regarded as a promising proactive tool for groundwater management and decision-making.

Keywords: coastal aquifer; groundwater salinization; GALDIT; vulnerability; Rhodope

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1. Introduction

Groundwater constitutes the main source of fresh water globally. The percentage of Earth's population that resides and acts in a range of 65 km from the coastline is approximately 60%, which may indicate the overexploitation and the possible irrational management of coastal aquifers [1]. Severe salinization effects on groundwater systems are caused by seawater intrusion due to the coastal aquifer's overexploitation. Seawater intrusion is spotted across the world, mainly in coastal areas. Once established, salinization is rather difficult and costly to be mitigated. Therefore, proper proactive measures are essential to assess the susceptibility of an aquifer to seawater intrusion or salinization phenomenon in general and predict the possibility of being impacted; hence appropriate management measures are designed and deployed.

Previous research studies have used the original GALDIT method or modifications to assess groundwater vulnerability to salinization. In some cases, the GALDIT is applied in combination with other tools for integrated assessment. For example, in Kenya's Mombasa North coast's coastal aquifer, multiple approaches have been applied for groundwater quality control and seawater intrusion vulnerability. Among these methods, the GALDIT was applied to assess seawater intrusion [2]. Seawater intrusion was also examined in Jijel plain, North Algeria, by applying the GALDIT and the MODFLOW model—in a combined approach that examined vulnerability to seawater intrusion and potential future management scenarios related to groundwater level [3].

In the Mediterranean region, Zghibi et al. [4] applied the GALDIT method for seawater vulnerability assessment in the Korba region in northwestern Tunisia, emphasizing the need for modifications of weights and ratings in each study area to reflect better the unique characteristics in each case. The SEAWAT model was used for the detection of the extension of seawater intrusion and the investigation of four methods in an attempt to control this phenomenon in two different regions, the first in the shallow coastal aquifer of Gaza, Palestine, and the second one in the deep aquifer of Nile Delta, Egypt [5].

In the northeastern Mediterranean region, Kazakis et al. [6] investigated the seawater intrusion vulnerability in the coastal area of Epanomi (Greece) and the Po River lowland in Italy. Towards this aim, a modified GALDIT method, named GALDIT—SUSI (SUperficial Seawater Intrusion), was developed and applied to better identify seawater intrusion vulnerability by taking into account the influence of surface water bodies (lagoons, rivers, torrents and wetlands). Lepouri [7] applied the GALDIT and the GALDIT—AHP method to assess seawater intrusion vulnerability in the coastal area of Almyros (Greece), from 1992 to 2015. The GALDIT—AHP Mode was the most suitable method for assessing salinization in the study area.

Parizi et al. [8] presented two modifications of the GALDIT method to achieve a more realistic vulnerability assessment in three coastal aquifers along the southern coast of the Caspian Sea in the northern part of Iran. The first modification was the replacement of the (L) factor of the height of groundwater level above sea level with the seaward hydraulic gradient (i) (so-called GAiDIT), and the second one was the consideration of the hydraulic gradient (i) as an additional parameter to the GALDIT method (so-called GALDIT-i). The original GALDIT method was also applied to identify the differences.

Another modification of the GALDIT method is combining the Wilcoxon non-parametric statistical test and the entropy method to modify the original GALDIT method's rates and weights. Hence, the developed methods are the Wilcoxon-GALDIT, the GALDIT-entropy and the Wilcoxon-entropy method applied to Gharesoo-Gorgan Rood basin in the province of Golestan, Iran [9].

Recently in 2021, three different modifications of GALDIT emerged [10–12]. Kim et al. [10] developed a monthly GALDIT method in the coastal aquifer in South Korea. Specifically, the six parameters of the classic GALDIT were divided into static and dynamic parameters and 10-year-averaged data (2010–2019) of each month is used to implement the modified version. In this way, a seasonal variation of vulnerability is obtained taking into account the temporal variations. Salem and Hasan [11] applied the original GALDIT method and a modified one for the Pleistocene aquifer at the West Nile Delta and emphasized differences in the two final vulnerability maps. Bordbar et al. [12] modified the GALDIT weights with a genetic algorithm (GA) and the frequency ratio (FR) rates. The vulnerability-modified index showed a strong correlation (Pearson correlation coefficient up to 0.76) with the TDS. Consequently, a more realistic view of seawater vulnerability assessment was achieved.

Sadeghfam et al. [13] investigated the seawater intrusion by two graphical techniques. Specifically, the expanded Durov Diagram (EDD) and the Hydrochemical Facies Evoloution Diagram (HFE-Diagram) were used to identify the spatial distribution of samples that affected by seawater intrusion. Samani et al. [14] applied soft computing methods (artificial neural network, fuzzy logic, adaptive neuro-fuzzy inference system, group method of data handling and least-square support vector machine) to predict the groundwater level in the unconfined aquifer of Qazvin in Iran. The prediction was made for one-, two-, and three-month ahead with emphasis on specific meteorological components and aiming to achieve the sustainable development goals and an integrated water resources management.

The original GALDIT and all consequently modified versions focus on the vulnerability to seawater intrusion. To the best of the authors' knowledge, none of these methods deals with the vulnerability to salinization, which could be driven by additional sources/processes, in addition to or supplemented by seawater intrusion. To this goal, we propose a modification of GALDIT that considers the synergetic impact of salinization due to the various potential sources.

Hence, the objective of this study is to develop a new modification of the original GALDIT method for vulnerability assessment of the cummulaice salinization caused by potentially overlapping processes (e.g., trapped saline lenses, irrigation return, geothermal impact, rock leaching). In addition, some of the original GALDIT classes could be improved to fit the specific conditions of the Mediterranean and provide a more representative and integrated approach to assessing groundwater vulnerability to salinization. Overall, the main goal of the paper is to introduce a more representative and accurate method of assessing the salinization phenomenon as a whole, adjusted to the specific conditions of the Mediterranean. However, the generic framework could be easily applied worldwide, providing better results regarding vulnerability assessment.

2. Materials and Methods

2.1. Study Area

The study area is located in the coastal Rhodope region (NE Greece). It extends between the Vistonida and Ismarida Lakes and covers approximately an area of 110 km^2. It is a lowland to a hilly area with steep slopes at the western and eastern boundary of the study area (boundary with Vistonida Lake and Ismarida Lake, respectively), creating an upgrade with a mean altitude of 10 m–15 m.

According to Koppen's classification, the climate is Mediterranean coastal with mild winters and hot and dry summers, whereas most rainfall is lost with surface runoff and evapotranspiration [15]. The mean annual precipitation was 555.3 mm for the period 1954–2005 and the range of mean temperatures was 13.6 °C to 15.6 °C for 1996–1999 [1].

It is mainly an agricultural permanently irrigated area, except for a small coverage at its northeastern part. Pastures and industrial units are also located in the northeast, as well as scattered settlements and marshes close to water bodies [16]. Various lagoons lie in the south, and two dominant lakes are the physical boundaries that delineate the study area. The hydrolithology is characterized by frequent altrerations of clay, sand and cobbles, so the hydraulic conductivity vary depending on the thickness of the above sediments. A hydrolithological map presented in Figure 1, where the unconfined aquifer presented with pink color and the confined one with the light blue. The semi-confined aquifer characterized by a mean thickness of 35 m and limited hydraulic conductivity, and the confined one by a thickness between 50 m to 100 m with significant water supplies [17]. The hydraulic connection of aquifers was odserved in the area of Mesi and the degree of their hydraulic continuity depends on the character and the thickness of the interbedded confining units [18]. The present study assesses the salinization vulnerability of the uppermost semi-confined aquifer. However, it should be noticed that due to tectonics and complex stratigraphy, the two aquifers can be unified into a common groundwater system. According to Galazoulas et al. [17], electrical conductivity generally exceed 1 mS/cm at the largest portion of the study area with the maximum of 45 mS/cm at the inlet of Vistonis lagoon.

The stratigraphic sequence in the study area consists mainly of interbedded clay, silt, sandstone and conglomerate from Eocene to late Miocene [18] (Figure 2). According to Petalas and Lambrakis [18], in the basement of the sequence is a thick layer of clay, which consists of the lower impermeable boundary of the confined aquifer. This grey-greenish clay is at a lower depth northwest of the study area due to tectonic causes that reduce the thickness of the Upper Miocene sediments [19]. The confined aquifer is of

Upper Miocene age and consists of sand, gravel and cobbles with interbedded clay layers. Overlying the confined aquifer is a thin layer of clay that constitutes the upper impermeable boundary of the aquifer. At the top of the sequence, loose sandstones, siltstones and fine-grained sediments are deposited, constituting the semi-confined aquifer of the study area. Two geological cross-sections presented for the study area (Figures 3 and 4), that clearly demonstrates the complex hydrogeology. The boundary condition in the inlet of Vistonida Lake is presented in Figure 4, illustrating the entrance of saline water into the groundwater system.

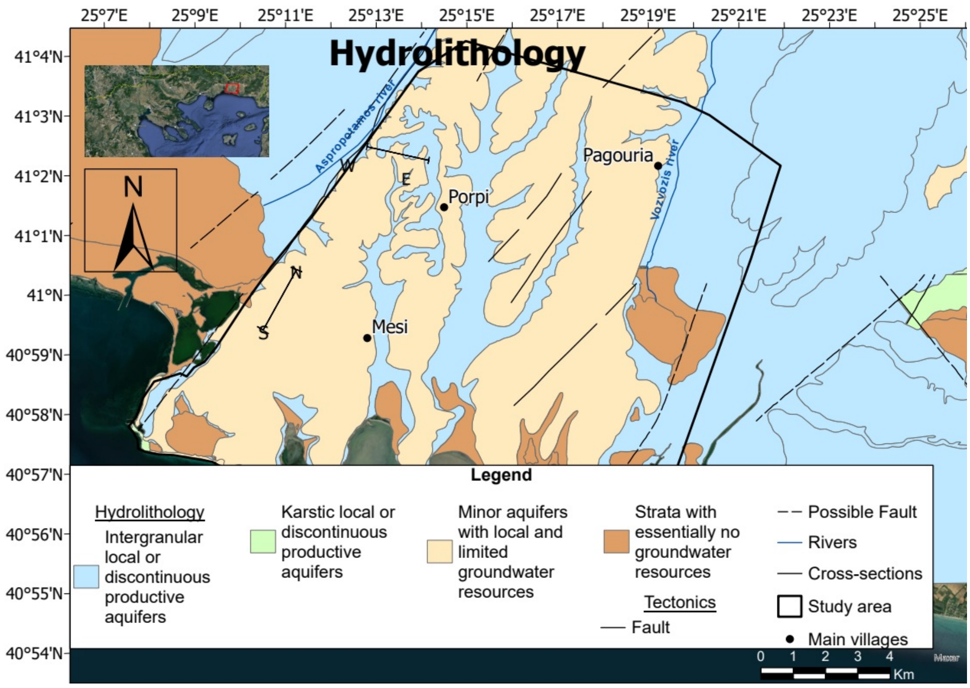

Figure 1. The hydrolithology of the study area.

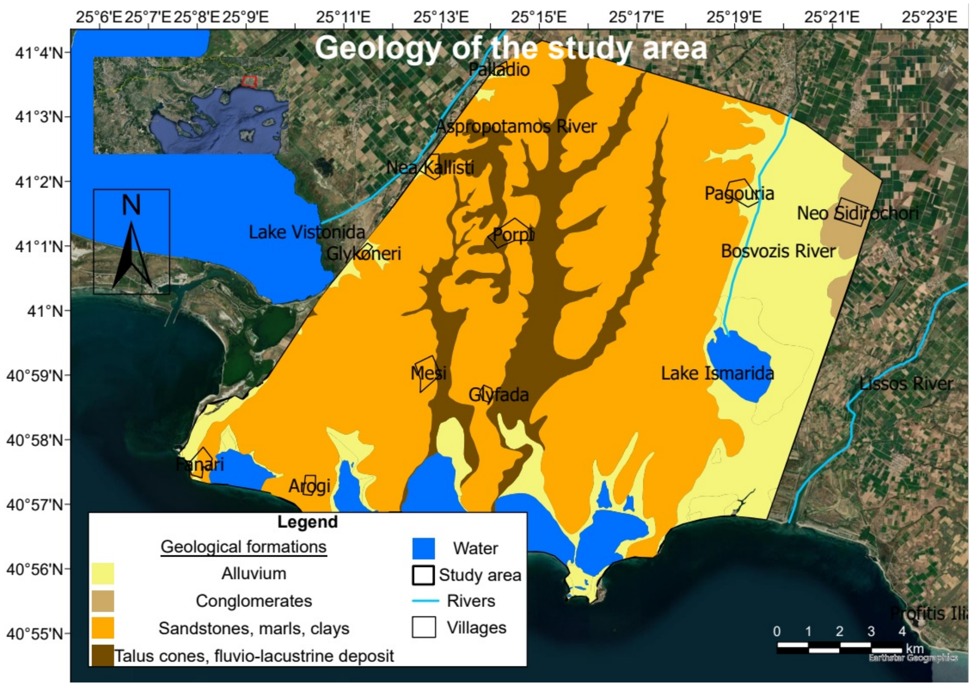

Figure 2. The geological formations of the study area [20].

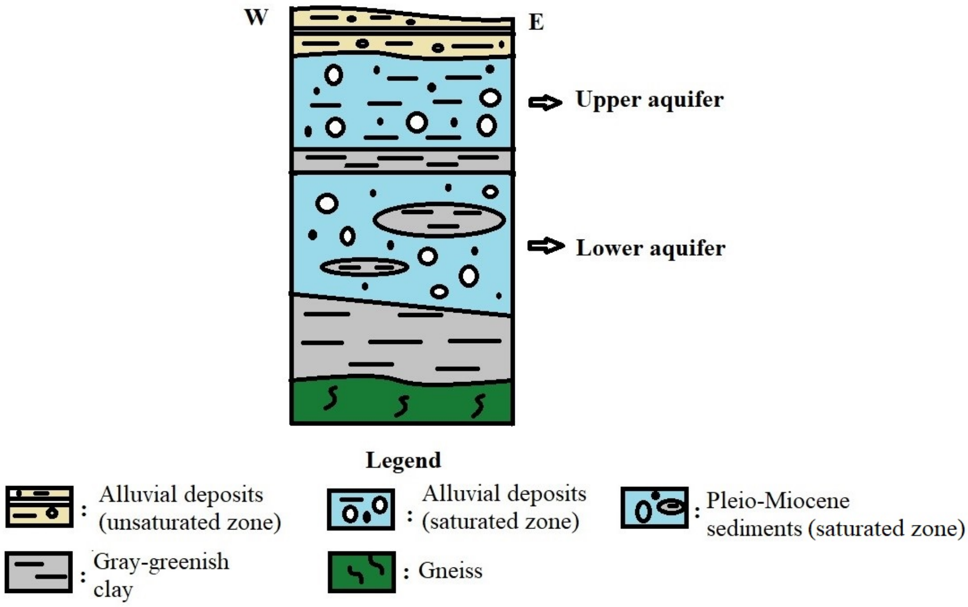

Figure 3. A geological cross-section (West-East) for the study area.

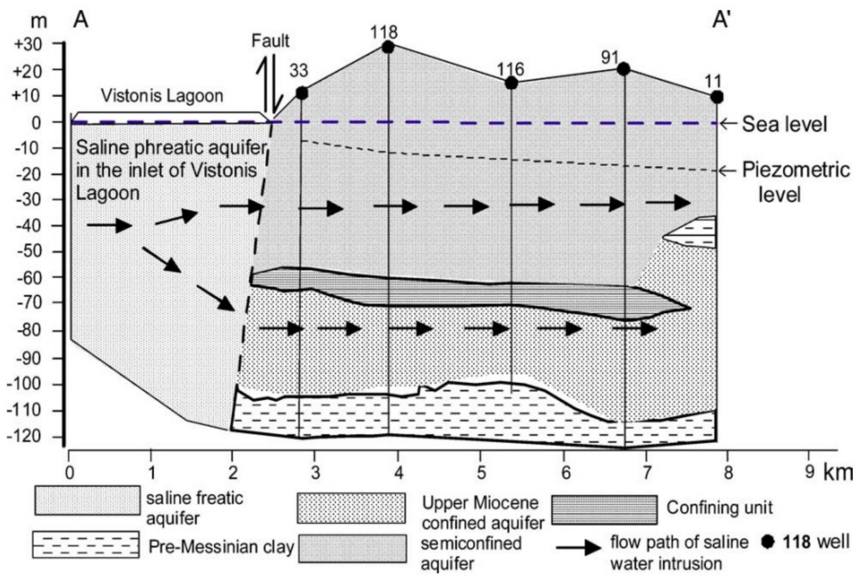

Figure 4. Hydrogeological cross-section (South-North) adopted by Petalas and Lambrakis [18].

A system of two normal faults with NE—SW direction defines the eastern and western boundaries, which uplifts the intermediate region [19]. These faults pose a significant role in the groundwater flow, as it finds passage to move from one region to another. Recharge is performed by lateral inflows, mainly at the W-NW boundaries of the study area through the Kompsatos River alluvial fan. The latter recharges the confined aquifer through two major axes, one south of Glykoneri and one close to the Nea Kallisti village. Also, a cone of depression is observed close to Porpi village, where the groundwater flow lines converge [17].

The Rhodope coastal area was selected for testing the newly introduced method, as it is characterized by multiple salinization sources even in notable distance from the shore. Thus, the potential impact (addressed by the GALDIT-I method as the new I factor) caused by several and overlapping salinization processes could be investigated. However, the architecture of the new method is not biased towards specific study areas, as it can be applied with success regadless of the specific site characteristics. That constitute the new method, a global approach for the assessment of vulnerability to groundwater salinization which has been further optimized by the inclusion of new weights and classes.

2.2. Data

The data for this study is mainly based on an extended literature review for the area (Table 1) and supplemented by field observations. The samples were taken with representative spatial distribution. In each sampling point two samples were taken, one for anion and cation analyses and the other for trace elements analyses. The chemical analyses were conducted in the SWRI (Soil and Water Resources Institute) Lab with the ISO standards. Also, in situ measurements were taken for the physicochemical parameters (pH, Temprature, E.C.) with the appropriate equipment. The recorded data was initially homogenized (e.g., databases, maps, units, etc.) and pre-checked for potential errors. Then, it was classified according to the GALDIT factor intended to be used and digitized (if needed).

Table 1. Data sources for the appropriate information for the specific study.

Geology, hydrology, tectonics	Petalas (1997), Petalas and Diamantis (1999), Petalas and Lambrakis (2006), Kallioras (2008), Petalas et al. (2009)
Land use	Corine 2018
Groundwater occurrence (G)	Petalas and Lambrakis (2006), Galazoulas et al. (2015)
Aquifer hydraulic conductivity (A)	Petalas (1997), Kallioras (2008)
Groundwater level above sea level (L)	Petalas (1997), Kallioras (2008), Petalas et al. (2009), Kallioras et al. (2010)
Distance from the shore (D)	Buffer tool of ArcGIS
Impact of existing status of seawater intrusion/salinization (I)	Field campaigns
Thickness of the aquifer (T)	Kallioras (2008), Galazoulas et al. (2015)

2.3. The Original GALDIT Method

GALDIT is a numerical ranking method based on index and overlay techniques for assessing vulnerability to seawater intrusion. A decision-making process is executed to weigh and prioritize the factors and a numerical calculation is followed for seawater intrusion vulnerability [21]. The original GALDIT method [22] is based on six hydrogeological parameters: groundwater occurrence (G), aquifer hydraulic conductivity (A), groundwater level above sea level (L), distance from the shore (D), the impact of the existing status of seawater intrusion (I) and thickness of the aquifer (T). Each parameter is assigned a weight factor representing the relative influence of seawater intrusion, ranging from 1 to 4 and a rating that classifies the vulnerability from low (2) to high (10) values (Table 2). The final GALDIT index that assesses vulnerability to seawater intrusion is calculated from Equation (1) and ranges from 5 to 10:

$$\mathrm{GALDIT_{index}} = \frac{\sum_{i=1}^{i=6}(\mathrm{Wi} \times \mathrm{Ri})}{\sum_{i=1}^{i=6}\mathrm{Wi}} \quad (1)$$

where W_i is the weight for each factor and R_i is the rating of each factor. If the GALDIT index is less than 5, the vulnerability is low. Moderate vulnerability is shown in the range of 5 to 7, and a GALDIT index equal to or higher than 7.5 indicates high vulnerability. The raster calculator tool of ArcGIS Pro was used to calculate the GALDIT index, combining the six interpolated with IDW maps of factors.

Table 2. Weights, ranges and rating of six factors for the original GALDIT method.

Factor	Weight	Range	Rating
G	1	Confined aquifer	10
		Unconfined aquifer	7.5
		Semi-confined aquifer	5
		Bounded aquifer	2.5
A (m/d)	3	<5	2.5
		5–10	5
		10–40	7.5
		>40	10
L (m)	4	>2	2.5
		1.5–2	5
		1–1.5	7.5
		<1	10
D (m)	4	>1000	2.5
		750–1000	5
		750–500	7.5
		<500	10
I (ppm)	1	<1	2.5
		1–1.5	5
		1.5–2	7.5
		>2	10
T (m)	2	<5	2.5
		5–7.5	5
		7.5–10	7.5
		>10	10

2.4. The Modified GALDIT-I Method

A modified version (GALDIT-I) of the GALDIT method was developed to acquire more representative outcomes. The general methodological framework is provided in the diagram of Figure 5. The modifications, compared to the original method, are mainly four: (a) the different weighting factors with the aid of the Analytical Hierarchy Process (AHP), (b) the modification of classes of key parameters, (c) the use of a different indicator (TDS) for the estimation of the Impact factor and d) the concept of groundwater salinization instead of solely seawater intrusion.

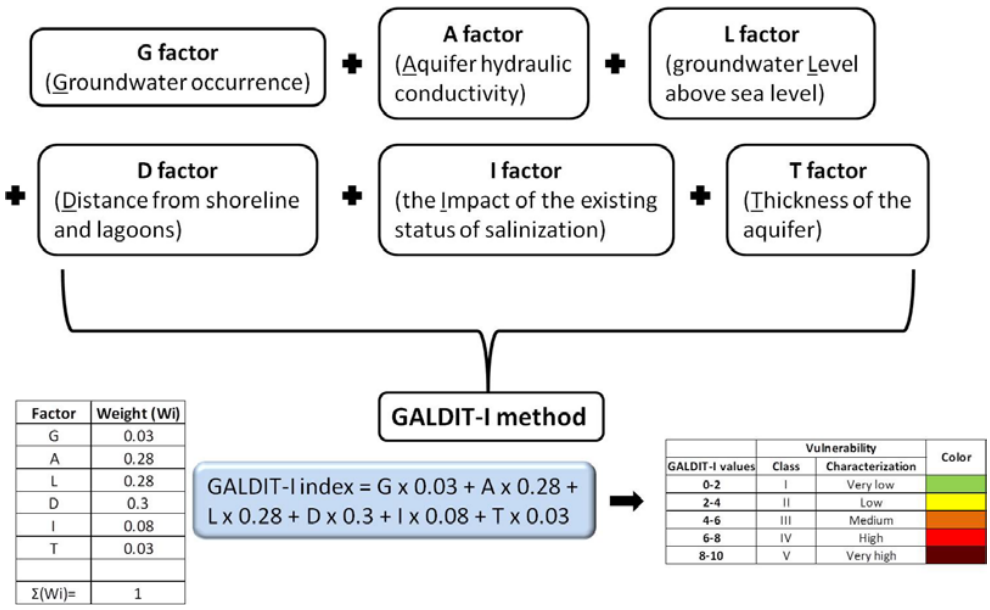

Figure 5. Diagram of the general methodological framework of the GALDIT-I.

The modification of weights and ratings was performed with the Analytic Hierarchy Process (AHP), a multi-criteria decision-making process that deals with real multidimensional problems developed by Saaty [23]. The AHP assumes that the problem can be described, the relationships and the interactions among its parts can be determined, and the comparisons among the parts of the problem can be done according to the final goal or purpose of the researcher. This method can use both qualitative and quantitative data and simplify complex problems through the hierarchical construction of the problem and the relevant comparisons among the factors.

The characteristic feature of the AHP method is that it scores the significance of each factor compared to the significance of another, based on binary comparisons through the Saaty's scale '. The Saaty's scale is an absolute numbers scale ranging from one (1) to nine (9). One (1), in Saaty's scale, reflects the equal importance between the two comparable factors and nine (9) the extreme importance of one factor compared to the other. Finally, a MxN matrix is created, where M is the number of criteria and N is the number of alternative activities (factors). The best alternative activity (for maximization problem) results from the Equation (2):

$$A = \max_i \sum_{j=1}^{M} w_j \times a_{ij},\ i = 1, 2, \ldots N \quad (2)$$

where a_{ij} is the value of the i-alternative activity as to the criterion j and w_j is the weight (significance) of the criterion j.

This method has increased subjectivity as it heavily relies on the participants' expert judgement. However, the subjectivity may be controlled by the Consistency Ratio (CR) calculated from Equation (3):

$$CR = \frac{CI}{RI} \quad (3)$$

where CI is the Consistency Index and RI is the Random Index, determined by the number of factors. A Consistency Ratio equal to or less than 0.10 means the matrix has low inconsistency. A Consistency Ratio from 0.10 to 0.20 considers acceptable, but a value more than 0.20 means the matrix has high inconsistency and the problem should be reviewed [24].

This research used the knowledge of experts in hydrogeology and hydrogeochemistry to derive new weights of critical factors.

The AHP method was applied and the results (Table 3) showed that the most important factor is the distance from the coastline (or lagoons, if existing, likewise in the examined study area) (w_D = 0.298), followed by the aquifer hydraulic conductivity and the groundwater level above sea level follow in descending order (w_A = 0.283 and w_L = 0.275, respectively). The priority values of six factors of the GALDIT method arose from the decision matrix presented in Table 4. The Consistency Ratio (CR) was calculated at 1.5%, indicating insignificant inconsistency. Classes of specific parameters are also modified to represent the specific characteristics of coastal aquifers in the Mediterranean region. Coastal aquifers, especially in the Mediterranean, are usually characterized by significantly lower groundwater levels below the sea level (L) due to overexploitation—hence, the classes of the original GALDIT method are not representative and need to be modified. In addition, the heterogeneity of the geological formations that form the aquifer layers makes necessary the modification of classes for the factor "A" to represent clearly the frequent alterations in the hydraulic conductivity (A) values. This also applies to the thickness of the aquifer (T), as alteration of thickness is observed in its different spots. The modified weights, ranges and ratings are presented in Table 3.

Table 3. Weights, ranges and rating of six factors for the modified GALDIT method.

Factor	Weight	Range	Rating
G	0.032416	Confined aquifer Unconfined aquifer Semi-confined aquifer Bounded aquifer	8 6 4 2
A (m/d)	0.283237	<5 5–10 10–30 30–50 >50	2 4 6 8 10
L (m)	0.27552	>0 0–(−5) (−5)–(−15) (−15)–(−30) >(−30)	2 4 6 8 10
D (m)	0.298887	>4000 4000–3000 3000–2000 2000–1000 <1000	2 4 6 8 10
I (mg/L)	0.07944	If TDS 1000–3000: then buffer <250 m, 250–500 m, 500–750 m If TDS 3000–10,000: then buffer <250 m, 250–500 m, 500–750 m, 750–1000 m If TDS >10,000: then buffer <250 m, 250–500 m, 500–750 m, 750–1000 m, 1000–2000 m	6,4,2 8,6,4,2 10,8,6,4,2
T (m)	0.030499	<5 5–15 15–25 25–35 >35	2 4 6 8 10

Table 4. The decision matrix of the AHP method.

G	A	L	D	I	T
1.00	0.14	0.13	0.11	0.33	1.00
7.00	1.00	1.00	1.00	5.00	8.00
8.00	1.00	1.00	1.00	4.00	8.00
9.00	1.00	1.00	1.00	5.00	9.00
3.00	0.20	0.25	0.20	1.00	4.00
1.00	0.13	0.13	0.11	0.25	1.00

The six parameters of the original GALDIT method remained the same, except for the impact of the existing status in seawater intrusion (I), which in the modified version turned into impact from groundwater salinization (I). In addition, the I factor of the original method is calculated by the Revelle coefficient. To acquire more accurate and representative outcomes, the I factor of the modified GALDIT method considers the values of Total Dissolved Solids (TDS), which are regarded as a more representative fingerprint for groundwater salinization. The modified I factor is calculated by a buffer zone from the established impact in relation to the variation of the TDS values, according to a modified classification by Eyankware et al. [25].

The number of buffer zones and the definition of their range is empirical. They aim to provide a semi-quantitative approach and emphasize areas with a high concentration of TDS, as the goal of this modification is to identify vulnerable to salinity areas from various salinity sources.

The classes of the GALDIT index were also modified to capture the impact of the vulnerability in more detail, ranging from very low to very high (GALDIT-I index from 0 to 2 indicates a very low vulnerability in salinization, 2 to 4 low vulnerability, 4 to 6 medium vulnerability, 6 to 8 high vulnerability and 8 to 10 very high vulnerability).

3. Results and Discussion

3.1. Calculation of Factors for the GALDIT-I Method

All factors have been calculated in a uniform raster grid of 50 × 50 m using ArcGIS Pro® software. The chosen spatial interpolation method, when needed, was the IDW (Inverse Distance Weighting) method, which has been successfully applied in similar applications [26]. Below follows the detailed description for each one of the GALDIT-I factors.

The G factor refers to the aquifer type that affects the groundwater's salinization due to its inherent characteristics. By definition, the confined aquifer is the most vulnerable due to limited recharge conditions that may exacerbate or trigger the salinization phenomenon. The confined aquifer type covers the entire study area without spatial deviations and sets a rating of 8 for the G factor.

The A factor refers to the hydraulic conductivity of the geological formations that form the aquifer layer. It is an important factor in determining the aquifer's pumping rate. The high hydraulic conductivity is usually related to intensive pumping rates that may lead to the overexploitation of the aquifer. A factor ranges from 0.80 m/d to 192 m/d in the study area, indicating the frequent alterations of geological formations. The rating for the GALDIT-I method ranges from 2 to 10 for low and high hydraulic conductivity values, respectively.

The L factor is the piezometric level of groundwater above sea level and is important as it defines the interface position. A high piezometric head pushes the interface towards the sea, preventing seawater intrusion. The reverse is observed when the piezometric head is low. Measurements of groundwater level are crucial for the vulnerability assessment of salinization. A combination of data from 53 boreholes was used to calculate the L factor that ranges from −41 m in the central area due to overpumping to 1 m in the northwest, a recharge area from Kompsatos River. The rating ranges from 2 to 10 for the areas with hydraulic head above the sea level (>0 m) and for the areas with hydraulic head 30 m and more below the sea level (≥30 m), respectively.

The D factor is the distance from the coastline (or other saline water bodies) and is also crucial for the vulnerability assessment of salinization. The buffer tool of ArcGIS Pro was used for calculating the distance from the sea and lagoons, according to the modified classification of the proposed method. The D factor ranges from 0 m close to sea and lagoons, with rating 10, to 14,500 m in the north boundary of the study area and rating 0.

The I factor, accounting for the salinization impact in the study area, was calculated according to the ground-truth values of three sampling campaigns (unpublished data) between June 2020 and July 2021. The elevated TDS values (especially those far from the coastline) delineated hot spots of salinization that should be related to additional factors (other than seawater intrusion), such as trapped saline lenses and deep brines. Those are well described by previous researchers [1,17,18]. Based on that spatial delineation and the classification of Table 4, a buffer zone was set to define the impact of salinization around these spots. Groundwater flow has not been considered in the orientation of the buffer zones to avoid complexity, as in the latter case, the addition of a spatially distributed model would be essential. Thus, in some cases, the impact of salinization (I factor) could be overestimated, as the current calculation assumes the hydraulic connection of all neighbouring points. However, in the sense of the "worst case" scenario, this is acceptable, as it offers further safety in cases of decision-making and planning. The TDS ranges from 340 mg/L (rating 2) to 11089 mg/L (rating 10) in the study area.

The T factor refers to the thickness of the aquifer, which varies due to the complex stratigraphy and tectonics. The T factor ranges from 10 m West of Ismarida Lake to 117 m East of Aspropotamos River and the rating ranges from 4 to 10 for the corresponding areas. The thickness's fluctuation from West to East indicates that the interbedded clay layers are more frequent in the eastern, where the normal fault uplifts the specific area.

3.2. Original GALDIT Method Results

The implementation of the original GALDIT method results in medium vulnerability for nearly the entire examined area, apart from the coastline, where high vulnerability values prevail (Figure 6). Nevertheless, it is obvious that the discretization of the original GALDIT method is rough and that nearly 80% of the study area is characterized as medium vulnerability with very limited spatial deviations.

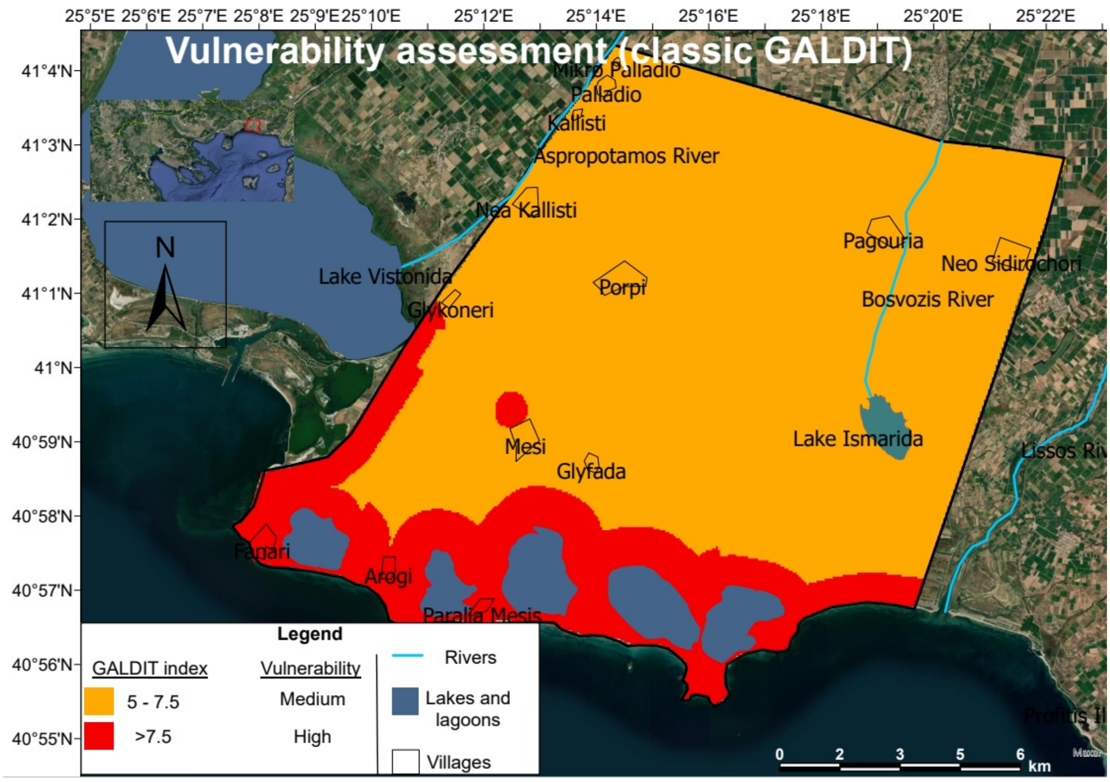

Figure 6. Calculation of original GALDIT index and vulnerability assessment map.

3.3. Modified GALDIT Method Results

The application of the GALDIT-I method resulted in the following thematic maps for each one of its factors with the aid of IDW interpolation (Figures 7 and 8).

The target aquifer is the uppermost semi-confined, which suffers from extended salinization phenomena (Figure 7, left). The hydraulic conductivity is generally low to medium due to the interbedded layers of clay, which have a significant thickness in specific areas (e.g., West of Ismarida lake) (Figure 7, right).

Concerning the piezometric head, the groundwater level is below sea level in almost the entire study area (Figure 8, up left). What is remarkable is the very low groundwater level in the northern and the northeastern area, where the groundwater level reaches thirty-one (31) meters below sea level, lower than is observed in the coastal zone (piezometric head up to fifteen meters (15) below the sea level). The very low groundwater level away from the coastline is due to the intensive pumping for agricultural purposes, as the groundwater near the shore is unsuitable for irrigation. The factor of distance from the shoreline and lagoons presents a zonal distribution, as the seawater intrusion phenomenon is eliminated away from the shore (Figure 8, up right). The effect of salinization in the study area shown by the corresponding map depicts specific spots away from the coast and lagoons with a high concentration of TDS, indicating possible salinity sources away from the coastline (Figure 8, down left). The final factor of aquifer thickness shows that the semi-confined aquifer's thickness is not stable across the area and ranges from five (5) to more than thirty-five (35) meters. However, in the largest part of its extent, the aquifer has a thickness of more than thirty-five (35) meters, increasing its vulnerability to salinization (Figure 8, down right).

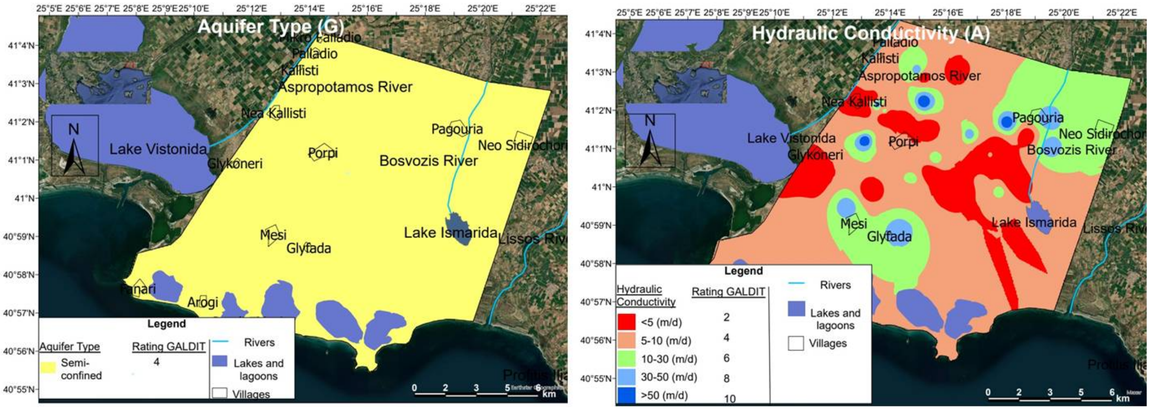

Figure 7. Thematic maps for the type of the aquifer (G) (**left**) and the hydraulic conductivity (A) (**right**) for the modified GALDIT method.

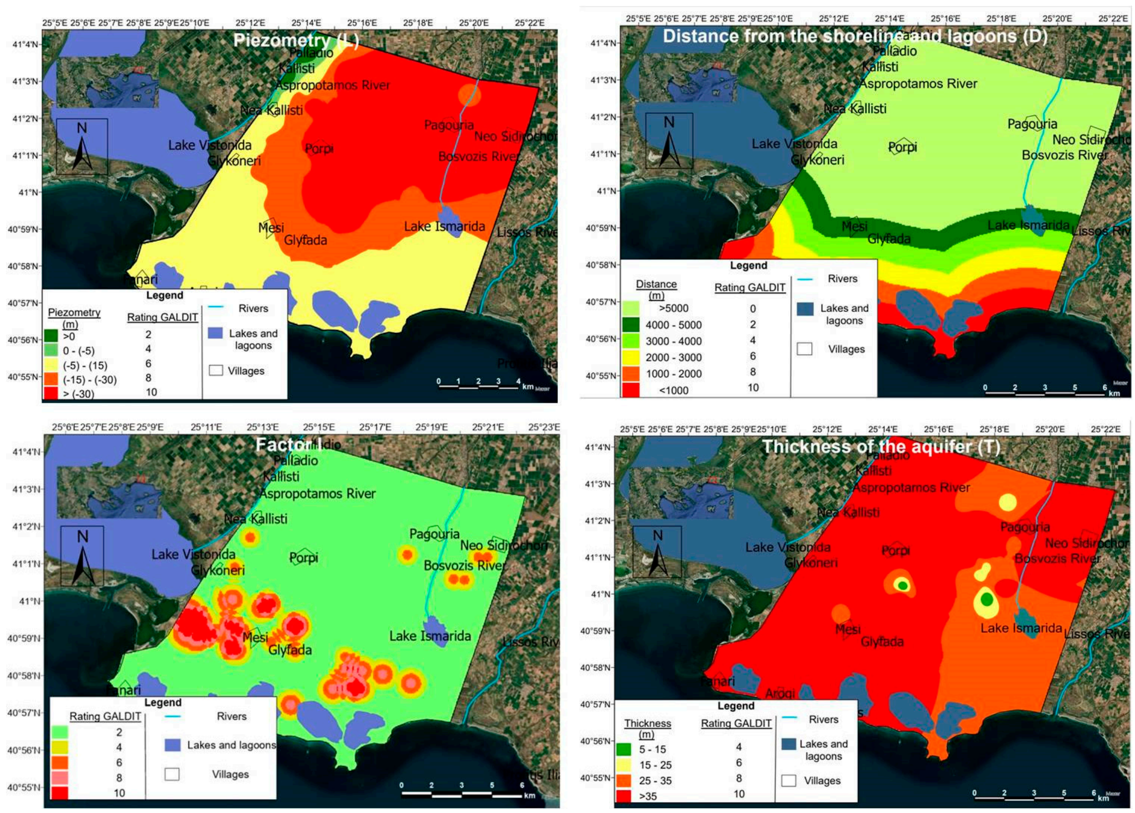

Figure 8. Thematic maps for the groundwater level above sea level (L) (**up left**), distance from the shoreline and lagoons (D) (**up right**), the impact of the existing status of seawater intrusion (I) (**down left**) and thickness of the aquifer (T) (**down right**) for the modified GALDIT method.

Finally, the modified GALDIT index was calculated using the raster calculator tool of ArcGIS Pro. So, the vulnerability map showed a more complex vulnerability image of the study area than the one acquired by the original GALDIT method (Figure 9).

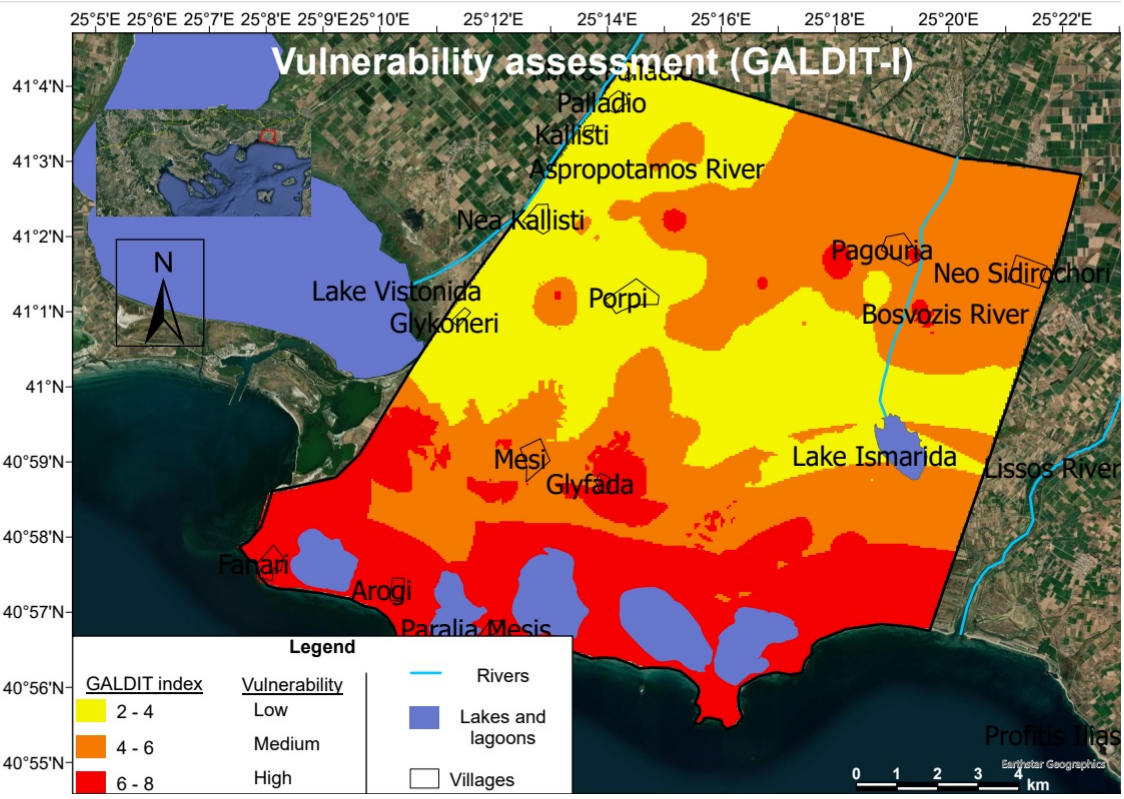

Figure 9. Calculation of GALDIT-I index and vulnerability assessment map.

Specifically, high vulnerability is spotted in the coastal zone, progressively reducing moving inland. However, high vulnerability hotspots and extensive medium vulnerability areas are depicted away from the shoreline, indicating salinity sources that may influence the chemical composition of groundwaters. These salinity sources may be the irrigation water return and trapped saline lenses, as indicated by previous researchers [27], verifying the outcomes of this new modification of the GALDIT method.

In contrast to the original GALDIT method that proposes a uniform medium vulnerability from the shoreline inland for the entire extent of the inland portion of the aquifer, the modified version yields a much more refined and spatially distributed condition for the aquifer vulnerability.

3.4. Verification of the Modified GALDIT Method

Correlation analysis has been used to verify the proposed modified GALDIT method. Firstly, the classification of water types based on the concentration of Cl^- has been modified and adapted to the Mediterranean region and presented in Table 5, according to Stuyfzand [28].

Table 5. Modified classification of water types according to the concentration of Cl^- (mg/L) [28].

Water Type	Oligo-saline	Fresh	Fresh-brackish	Brackish	Brackish-saline
Concentration of Cl^- (mg/L)	<30	30–250	250–1000	1000–6000	>6000

Five classes of Cl^- were created and correlated with each sample's vulnerability classes of the GALDIT index. The classes of the GALDIT-I index are also five, ranging from very low vulnerability to very high. Based on the above, the chloride concentrations have been related to the salinization classes, as seen in Table 6.

Table 6. Salinization classes for the correlation analysis.

Salinization Classes	Cl^- (mg/L)	Vulnerability
1	<30	Very low
2	30–250	Low
3	250–1000	Medium
4	1000–6000	High
5	≥6000	Very high

For the correlation analysis, the Spearman's correlation coefficient (r_s) was calculated by the Minitab v18 software ®, using Equation (4):

$$r_s = 1 - \frac{6 \times \sum d_i^2}{n \times (n^2 - 1)},\ i = 1, 2, \ldots n \quad (4)$$

where d_i is the difference between the two observations and n is the number of observations. The calculation of the Spearman's correlation coefficient showed that the correlation between the classes of Cl^- and the classes of GALDIT-I index was quite satisfactory (r_s = 0.665), indicating that the vulnerability assessment in salinization from the proposed modified GALDIT method was 66.5% correlated with the concentration of Cl^- in the study area. In addition, the difference between the salinization classes (based on Cl^-), as mentioned above, and the vulnerability classes of GALDIT-I index are calculated and shown in an interpolated with IDW (Inverse Distance Weighting) method map (Figure 10).

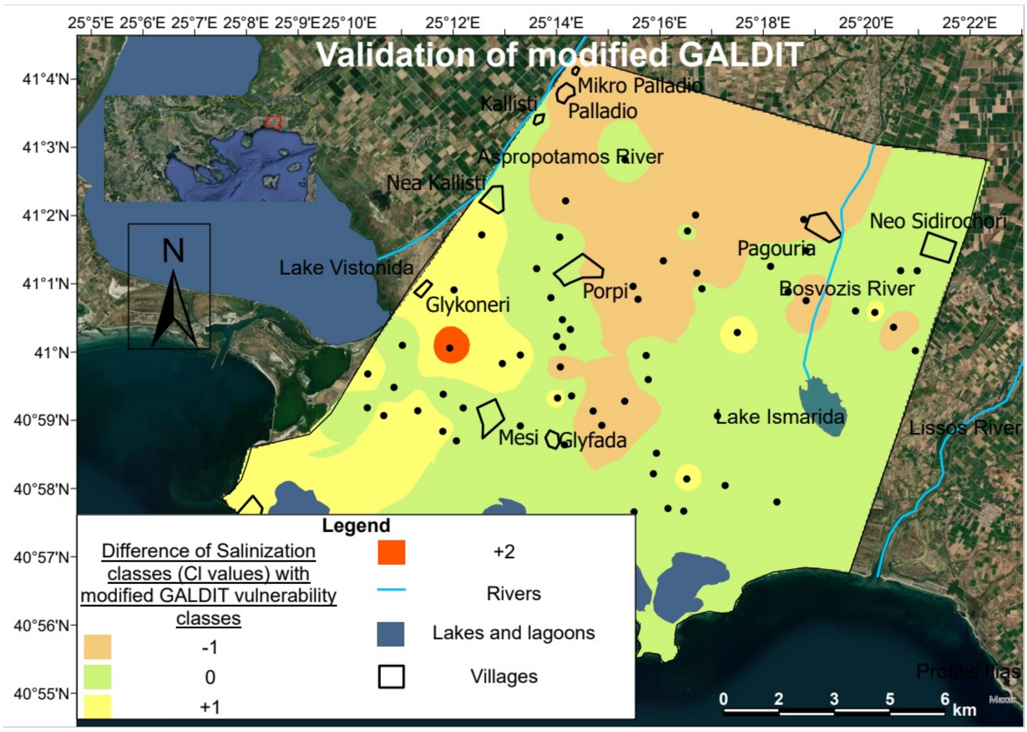

Figure 10. The difference of salinization classes (Cl^- values) with modified GALDIT vulnerability classes.

According to that, the vulnerability class of the GALDIT-I index perfectly correlated with the salinization class at a rate of 58.73%, as their difference was calculated as zero (0). That means that 58.73% of the sampling points present no difference (perfect match) between the two associated features, indicating that the salinity assessment and the concentration of Cl^- were fully correlated. A 20.63% of the sampling points present one (±1) class difference, which is a very good match. Overall, 79.36% present very good to perfect match, indicating the successful validation of the method as performed in Tziritis et al. [26].

Error criteria was also calculated to better understand the model's ability. Specifically, RMSE (Root Mean Squared Error), MAE (Mean Absolute Error), Eff (Model efficiency) and IA (Index of Agreement) was calculated and presented in Table 7.

Table 7. Error criteria for the GALDIT-I method.

Error Criteria	Value
RMSE	0.68
MAE	0.43
Eff	0.46
IA	0.81

Table 7 shows that the error criteria was quite good and especially the Index of Agreement (IA). The latter indicates the very good match (81%) between the salinization classes based on concentrations of Cl^- and the vulnerability classes from the GALDIT-I method. An additional method to verify this, is the simple regression method, that was made between the concentration of Cl^- and the vulnerability classes of GALDIT-I. The *p*-value (*p*-value = 1.18×10^{-7}) was much smaller than the significance level (α = 5%), so the impact of the concentration of Cl^- on the vulnerability classes of GALDIT-I method was statistically important. The summury output of the regression was presented in Tables 8–10.

Table 8. Regression analysis statistics.

Regression Statistics	
Multiple R	0.609
R Square	0.371
Adjusted R Square	0.361
Standard Error	0.594
Observations	63

Table 9. ANOVA of the simple regression analysis.

ANOVA					
	df	**SS**	**MS**	**F**	**Significance F**
Regression	1	12.69170015	12.692	35.95796269	1.18478×10^{-7}
Residual	61	21.53052207	0.353		
Total	62	34.22222222			

Table 10. Regression statistics and confidence interval.

	Coefficients	Standard Error	t Stat	*p*-Value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	2.52043984	0.09683957	26.027	9.89039×10^{-35}	2.326797155	2.71408253	2.326797155	2.71408253
Cl	0.000411559	6.86333×10^{-5}	5.9965	1.18478×10^{-7}	0.000274318	0.0005488	0.000274318	0.0005488

The occurring deviations between the measured Cl^- values and the GALDIT-I classes may be be explained as: (a) uncertainty due to the selected range of Cl^- classes, (b) effect from the spatial interpolation method applied, (c) additional sources of Cl^- (e.g., septic tanks) that may change the conservative character of the parameter and, (d) impact of other (than the focal semi-confined aquifer) systems, such as the deeper confined aquifer of better quality which (around Porpi area) is locally hydraulically connected with the semi-confined aquifer to a unified system.

3.5. Discussion

GALDIT is a widespread and perhaps the most well-established seawater intrusion vulnerability assessment method and has been applied globally for several years. However, the salinization effect may be triggered by sources other than seawater intrusion, which are underestimated (or not considered) by the original GALDIT method. As a result, well known and identified salinization sources may be overlooked, thus leading to partial assessment of the salinization potential, which in turn result in inefficient protection of the assessed groundwater system. The finer discretization of the vulnerability and the inclusion of the total concept of salinization (instead of seawater intrusion alone) may be successfully tackled by the new proposed GALDIT-I method. It's considerably improved performance has been successfully validated by the comparison of the outcome (Spearmann r_s of the vulnerability classess vs. Cl^- concentrations) between the original (31.4%) and the modified (66.5%) methods.

From that perspective, the new proposed GALDIT-I method may be used as a robust, proactive tool in local or regional coastal area planning. Nevertheless, it should not be considered a stand-alone tool, since knowledge of the local conditions (geology, stratigraphy, hydrogeology) is always an essential parameter and should be considered when performing similar assessments. The use of the GALDIT-I method combined with the consideration of the local conditions as deduced by the knowledge on hydrogeochemical and hydrodynamic evolution, geometrical characteristics and the identified pressures and pollution sources, can lead to the synthesis of a reliable vulnerability map that clearly depicts the most vulnerable to salinization areas. In this way, appropriate measures may be compiled and applied, focused on the salinization vulnerability of the individual identified zones. Such measures could indicatively include upgrading to higher efficiency irrigation methods, shifting to lower water demands and even lower nutrient's needs crops that however offer high yield and market value, reverting to pumping schemes strictly abiding with the critical pumping rate of each well, and implementation of groundwater artificial recharge schemes. These are likely to reduce the stresses imposed to salinization prone aquifers focusing on the most vulnerable zones on the basis of the knowledge obtained by the GALDIT-I based map, thus contributing to salinization mitigation. The contribution of GALDIT-I could be decisive for rational and sustainable groundwater management, as this method allows depicting the areas that are vulnerable to various salinity sources, ability that is not offered by the original GALDIT method or its known modifications.

The comparative advancements and challenges brought about in the assessment of the factors identified in the original and the proposed modified GALDIT methods are tabulated for ease of reference in the following Table 11.

Table 11. Challenges phased and/or advancements achieved by the GALDIT-I method.

GALDIT Factors	GALDIT-I Factors	Challenges and/or Advancements
Groundwater occurrence (G)	Groundwater occurrence (G)	No difficulties/challenges or advancements
Aquifer hydraulic conductivity (A)	Aquifer hydraulic conductivity (A)	Better capture of the complex hydrogeological regime
Groundwater level above sea level (L)	Groundwater level above sea level (L)	Adapted to the Mediterranean characteristics of low groundwater levels
Distance from the shore (D)	Distance from the shore and lagoons (D)	The distance from the lagoons was also considered
The impact of the existing status of seawater intrusion (I)	The impact of the existing status of salinization (I)	Uncertainty of Cl^- concentrations sufficiently addressed by the inclusion of TDS values. The potential for salinization impact overestimation is assumed as an early warning signal that safeguards against further salinization
Thickness of the aquifer (T)	Thickness of the aquifer (T)	Adapted to the Mediterranean characteristics of various aquifer'-s' thickness

4. Conclusions

The present study introduces a modified GALDIT (GALDIT-I) method for the assessment of groundwater salinization. Both methods (original and modified) have been applied to Rhodope coastal aquifer (Greece) which is subject to salinization risk due to variable causes. The comparison of the two methods, highlighted the significant advantages of the modified version which can be summarized in (a) assessment of the salinization phenomenon due to multiple potential sources, rather than solely by seawater intrusion, (b) optimized set of parameters (inclusion of I factor) to better capture the potential impact of salinization, (c) optimized weights and classes of the parameters which are better adjusted to the Mediterranean conditions and, (d) better and more representative discretization of groundwater vulnerability to salinization. Therefore, GALDIT-I apparently results to improved vulnerability assessments.

Hence, areas of elevated TDS values are now highlighted, regardless of their distance from the shoreline, as in the modified version modern sea water intrusion is not assumed to be the only salinization source, which is often the case in salt affected aquifers, weather coastal or not.

As with all methods, especially the index based ones, the GALDIT-I, presents inherent limitations, despite its pronounced assets. One of them is the uncertainty of Cl^- concentrations' origin. Cloride is a conservative element, thus inherently offering a rather conservative appraisal of salinization phenomena (worst case scenario approach). In actual fact Cl^- concentrations may be affected by factors other than modern sea water intrusion, such as lecheates of septic tanks and any other waste disposal site, amongst others, not overlooking the natural occurrence due to geogenic factors. Hence, the local conditions should also be thoroughly considered when applying the GALDIT-I method in order to avoid misinterpretations. Still, even this uncertainty may well be used in determining and pinpointing various sources of salinization that would have otherwise be disregarded. In addition, as mentioned in the previous paragraphs, the Impact factor (I) may overestimate the salinization impact, as it does not consider a spatially distributed approach but rather creates buffer zones around hotspots without considering hte flow direction. This simplification has been assumed reasonable, and an overall acceptable trade-off between reduced complexity, ease of application and representativeness of results, since it leads to an environmentaly conservative outcome that favors the presentation of the resources, especially considering their vulnerability. In coclusion, the slight overestimation of salinization impact that may result from the application of the method, acts as an early warning feature, thus safeguarding sustainability, prevention of further deterioration and overall earlier engagement of trend reserval measures when setting up strategic planning. Moreover, this potential local amplification of the salinization status may draw the attention of non-expert decision makers into considering on-time measures design and implementation.

Inherently, the assignment of specific weights in every considered factor may introduce subjectivity and therefore needs to be critically evaluated on a case per case manner to ensure minimazed deviations from the actual conditions of a specific aquifer system. In our test case validation of the obtained results against the produced field data and their hydrogeochemical interprentation prove the correctness of the selection, and since our test pilot is a typical Mediterranean coastal aquifer site, it is considered that the adopted weighting factors can be safely used at least across the region. Evidently, validation of the method in every system it is applied in, and fine trimming of the assumed factor values would act favourably, further increasing the accuracy and reliability of the method.

GALDIT-I has proved a robust, proactive tool for preliminary assessments of groundwater vulnerability to salinization and may be a valuable add-on to decision-making on land use and/or water resources management. It can pave the way for the characterization of areas and be integrated with other methods (e.g., hydrogeochemical analysis, groundwater modelling, etc.) into integrated assessment studies, regional policy-making and strategic planning.

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