USE OF A MODIFIED GALDIT METHOD TO ASSESS GROUNDWATER VULNERABILITY TO SALINIZATION – APPLICATION TO RHODOPE COASTAL AQUIFER (N.GREECE)

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Abstract

Aquifer overexploitation in coastal aquifers has led to seawater intrusion that causes severe salinization effects to the groundwater system. The most widespread method for assessing seawater intrusion vulnerability is the GALDIT method, with numerous applications globally. The present study applied an original GALDIT method and a proposed modified one to Rhodope coastal aquifer, and the differences were investigated. Initially, the original method was applied and identified an area of high vulnerability to salinization near the coast and medium in the rest. In the modified method, the medium salinization vulnerability is constrained in specific areas away from the shore, thus, suggesting that salinization in the study area is not attributed only to seawater intrusion, but also to other sources that may be identified by employing alternative hydrogeochemical study methods. Overall, the modified GALDIT method proved to facilitate groundwater vulnerability assessment to salinization more accurately and exhibited a more discrete spatial assessment.

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 (Kallioras, 2008). Severe salinization effects on the groundwater system are caused by the seawater intrusion due to the coastal aquifer's overexploitation. 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 and predict the possibility of being impacted so that appropriate management measures are designed and deployed. The most widespread method for assessing seawater intrusion vulnerability is the GALDIT method, modified in several applications globally to obtain optimum results. Parizi et al. (2019) 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 is the replacement of the factor of the height of groundwater level above sea level (L) with the seaward hydraulic gradient (i) (so-called GAiDIT), and the second one is the consideration of the hydraulic gradient (i) as an additional parameter to the GALDIT method (so-called GALDIT-i). Also, the original GALDIT method was applied to identify the differences. For the verification of the vulnerability maps, four indices are calculated (TDS, fraction of seawater (f_{sea}) into groundwater, groundwater quality indices (GQI) and length of the seawater intrusion into the aquifer section (L_x)). The produced vulnerability maps with the GAiDIT and the GALDIT-i method indicate a higher correlation by the pre-mentioned four indices specific to seawater intrusion than the original method. The original GALDIT method shows a moderate vulnerable zone in a limited length of the aquifers near the shore, whereas no high vulnerability is spotted.

In contrast, both GAiDIT and GALDIT-i methods indicated a high vulnerable zone in a significant area of the three aquifers. The outcome of the GAiDIT method was that the results were more reliable due to time-dependent anthropogenic changes, such as pumping. So, the utilization of both parameters L and i (GALDIT-i method) has more accurate results in vulnerability assessment, with the increase in several factors considered a drawback.

Another modification of the GALDIT method is the combination of the Wilcoxon non-parametric statistical test and the entropy method to modify the rates and the weights of the original GALDIT method. So, the developed methods are the Wilcoxon-GALDIT, the GALDIT-entropy and the Wilcoxon-entropy method for the Gharesoo-Gorgan Rood basin in the province of Golestan, Iran. The main control parameter of those methods was the concentration of TDS and the Pearson correlation coefficient was used to define the correlation between the vulnerability indices and the TDS concentration. The original GALDIT method had a Pearson index of 0.43, indicating a weak correlation, whereas the three modifications had a Pearson of 0.66, 0.51 and 0.75, respectively. Consequently, the Wilcoxon-entropy method was selected as the best method for the vulnerability assessment (Bordbar et al., 2019).

The GALDIT method's modifications become more frequent, as three different modifications are made in 2021 (Kim et al., 2021, Salem et al., 2021 and Bordbar et al. 2021). Kim et al. (2021) developed a monthly GALDIT method in the coastal aquifer in South Korea in an area of continuous increase in population. Specifically, the six parameters of classic GALDIT are divided into static (groundwater occurrence (G), aquifer hydraulic conductivity (A) and distance from the shore (D)) and dynamic (height to groundwater-level above sea-level (L), impact of existing status of seawater intrusion (I) and aquifer thickness (T)) parameters and a 10-year-averaged data (2010-2019) of each month is used for the implementation of the modified version of GALDIT method. In this way, a seasonal variation of vulnerability is obtained, and September was the most vulnerable month to seawater intrusion due to relatively low groundwater levels. Salem and Hasan (2021) applied the original GALDIT method and a modified one for the Pleistocene aquifer at the West Nile Delta and emphasized the differences in the two final vulnerability maps. The modification was the different weights used by the sensitivity analysis. As a result, a new modified GALDIT method was developed. The results show that the highly vulnerable area in seawater intrusion increased up to 15% with implementing the modified GALDIT method compared to the original one. Bordbar et al. (2021) also implemented the GALDIT method to assess seawater intrusion vulnerability at the Gharesoo-Gorgan Rood basin in Iran. The Pearson correlation coefficient was calculated to 0.47, showing a weak correlation between the GALDIT index and TDS concentration, indicating a need to improve the original GALDIT method for more accurate results. The weights are modified 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.

From this point of view, a new modification of the classic GALDIT method is developed to focus on vulnerability assessment in seawater intrusion and other cascading processes that may also trigger salinization (e.g. trapped saline lenses, irrigation return, geothermal impact, rock leaching). In addition, some of its classes could be improved to fit the specific conditions of the Mediterranean and provide a more representative and integrated approach to the assessment of groundwater vulnerability to salinization.

2. Methodology

2.1. GALDIT method

The original GALDIT method (Ferreira et al., 2005) is based on six 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 1). The final GALDIT index that assesses vulnerability to seawater intrusion is calculated from the Equation 1:

Equation 1: Equation for the GALDIT index

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

where W_i is the weight for each factor and R_i is the rating of each factor. The raster calculator tool of ArcGIS Pro was used to calculate the GALDIT index, combining the six interpolated with IDW maps of factors.

Table 1: Weights, ranges and rating of six factors for the original GALDIT method.

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

2.2 *Modified GALDIT method*

A modified version of the GALDIT method was developed to acquire more representative outcomes. The modifications, compared to the original method, are mainly four: a) the different weighting factors, based on an expert judgment procedure with the aid of the Analytical Hierarchy Process (AHP), b) the modification of classes of specific 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 seawater intrusion.

Table 2: 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 <250m, 250-500m, 500-750m If TDS 3000-10000: then buffer <250m, 250-500m, 500-750m, 750-1000m If TDS >10000: then buffer <250m, 250-500m, 500-750m, 750-1000m, 1000-2000m	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

The Analytic Hierarchy Process (AHP) (Teknomo, 2006) is used to modify weights, taking into account the specific features of the study area. The Consistency Ratio (CR) is used to find the consistency of the method calculated at 1.5 %, indicating insignificant inconsistency. The modified weights from this procedure are presented in Table 2. Classes of specific parameters are also modified to be more representative of the especially characteristics of coastal aquifers in the Mediterranean region (Table 2).

The six parameters of the GALDIT method remained the same, except for the impact of the existing status in seawater intrusion (I), in which the TDS replaced the Revelle coefficient. That was considered essential as the latter (due to Cl^- values) is prone to potential impacts from septic tanks or wastes, which might be misleading. In addition, the impact of the existing seawater intrusion is modified to impact salinization (including additional potential sources). Thus, the modified I factor calculates a buffer zone from the established impact according to the variation of the TDS values. Specifically, if the TDS values range from 1000 mg/L to 3000 mg/L, then a buffer zone less than 250m, 250m to 500m and 500m to 750m is created and is rated with 6, 4 and 2 respectively. If the TDS values range from 3000 mg/L to 10000 mg/L, then a buffer zone less than 250m, 250m to 500m, 500m to 750m and 750m to 1000m is created and is rated with 8, 6, 4 and 2 respectively. If the TDS values are more than 10000 mg/L, then a buffer zone less than 250m, 250m to 500m, 500m to 750m, 750m to 1000m and 1000m to 2000m is created and is rated with 10, 8, 6, 4 and 2 (Table 2). The number of buffer zones every time and the defining of their range are empirical and are aimed at emphasizing areas with high concentration of TDS, as the main goal of this modification of GALDIT method is to identify vulnerable to salinity areas, not only from seawater intrusion, but also from other salinity sources. Finally, the classes of GALDIT were modified to capture the impact of the vulnerability in more detail, ranging from very low to very high.
The final modified GALDIT index was calculated as the original GALDIT index, utilizing Equation 1.

2.3 Study area

The study area is located in the coastal Rhodope region (NE Greece). It extends between the lakes Vistonida and Ismarida and covers approximately an area of 110 km^2. It is 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 10m - 15m. There are two types of aquifers in the area. The semi-confined with a mean thickness of 35m and limited hydraulic conductivity and the confined one with thickness between 50m to 100m with significant water supplies (Galazoulas et al., 2015). The present study considers the salinization vulnerability of the upper semi-confined aquifer. The aquifer consists mainly of gravels, cobbles and sand with interbedded thin clay layers. It is mainly an agricultural area, so the water demands increases and is covered by the groundwater supplies.

3 Results and Discussion

3.1 Original GALDIT method

The implementation of the original GALDIT method proposes a uniform medium vulnerability from the shoreline inland, for the entire extent of the inland portion of the aquifer. High vulnerability is spotted at the coastline of the study area, indicating the part of the aquifer that is affected by seawater intrusion (Figure 1).

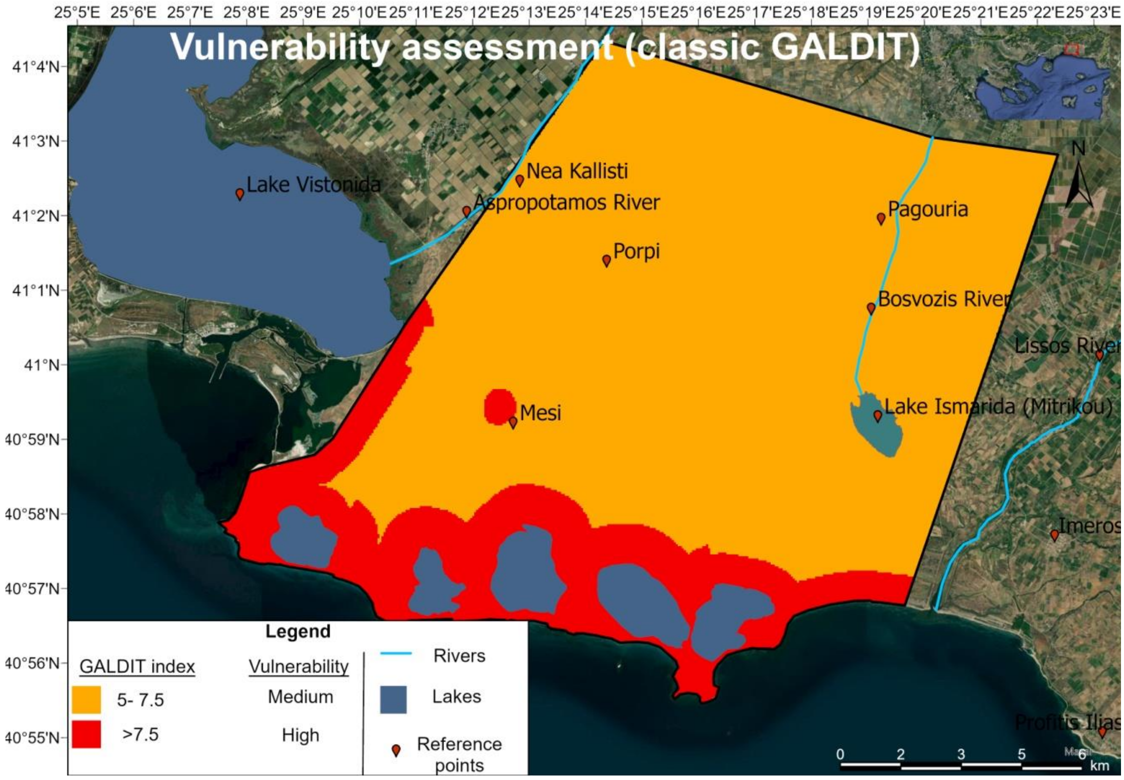

Figure 1: Calculation of original GALDIT index and vulnerability assessment map.

3.2 Modified GALDIT method

Thematic maps for each factor were created using the IDW interpolation method to calculate the modified GALDIT index and presented in Figure 2 and Figure 3.

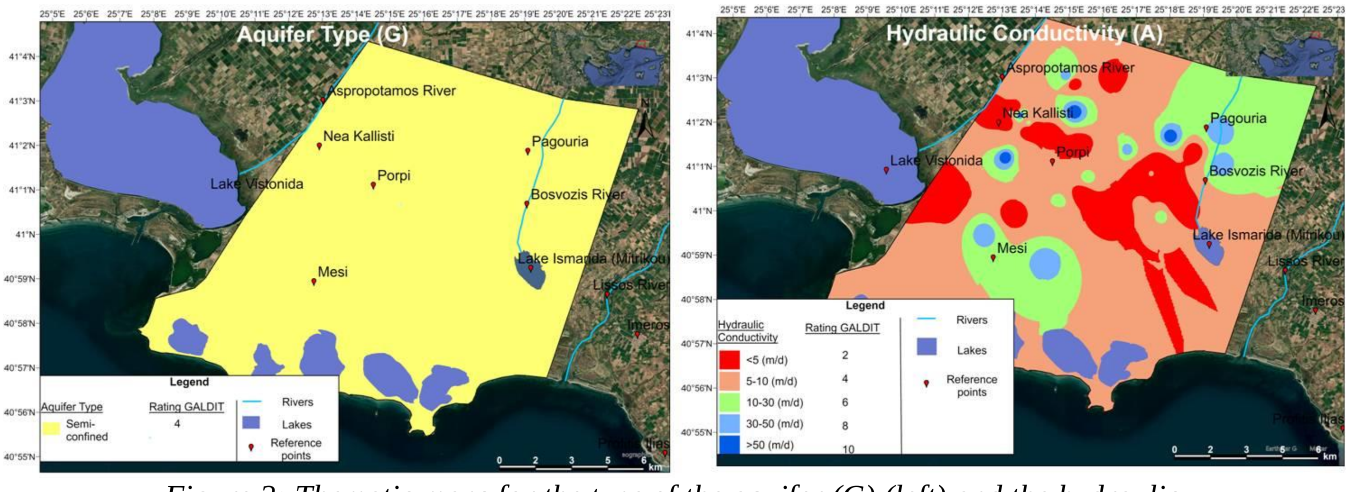

Figure 2: Thematic maps for the type of the aquifer (G) (left) and the hydraulic conductivity (A) (right) for the modified GALDIT method.

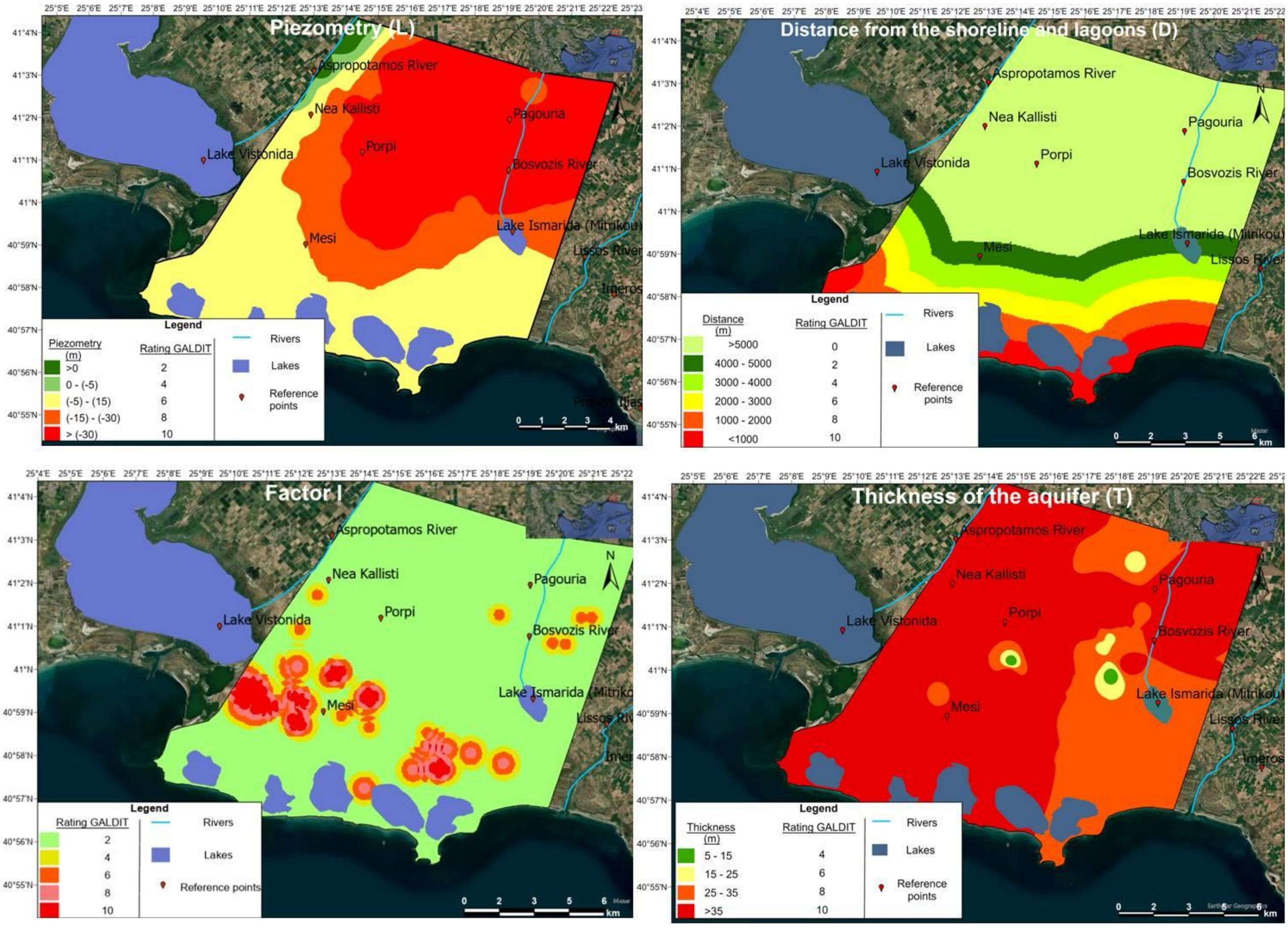

Figure 3: Thematic maps for the groundwater level above sea level (L) (up left), distance from the shoreline and lagoons (up right), impact of the existing status of seawater intrusion (I) (down left) and thickness of the aquifer (T) (down right) for the modified GALDIT method.

The final 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. Specifically, high vulnerability is spotted in the coastal zone and progressively reduces 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 (Petalas and Diamantis, 1999), verifying the outcomes of this new modification of the GALDIT method. The modified GALDIT index and the vulnerability map for the study area are presented in Figure 4.

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.

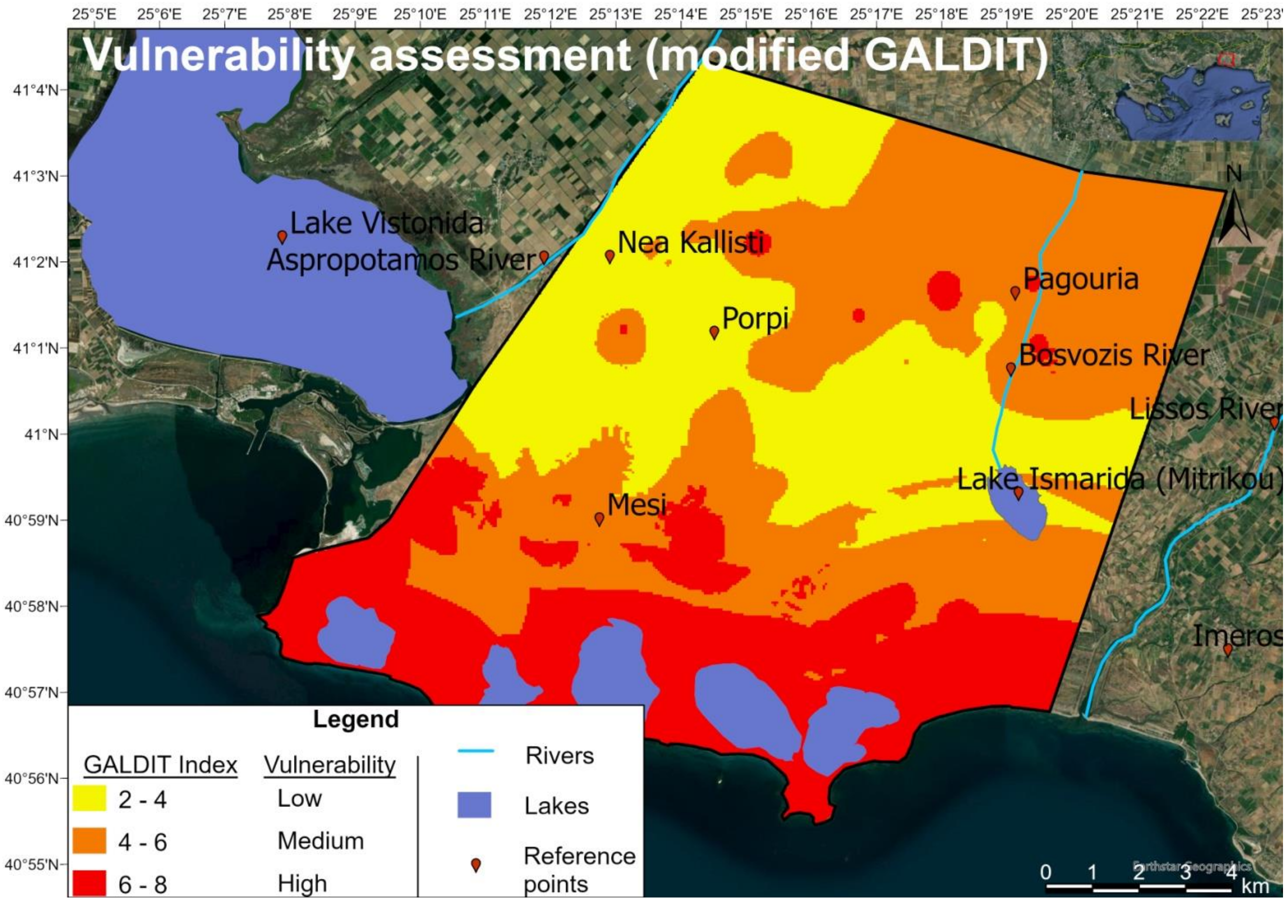

Figure 4: Calculation of modified GALDIT index and vulnerability assessment map.

4. Conclusions

The present study applied the original and the modified GALDIT method at Rhodope coastal aquifer. The first one indicates an area of high vulnerability to salinization near the shore and the rest of medium vulnerability to salinization. The modified GALDIT method indicates that the coastal zone is highly vulnerable to salinization. The original method suggests vulnerability progressively reduces moving inland, but high vulnerability hotspots and extensive medium vulnerability areas are depicted away from the shoreline, indicating other salinity sources except from seawater intrusion. This area is located northeast of the study area, in which previous researchers identified irrigation water return and trapped saline lenses as salinity sources that may influence the chemical composition of the groundwaters.
From the comparison of the two methods, it is evident that the modified version captures better the spatial distribution of salinization due to the optimized classification of parameters. Furthermore, the modified version can capture the effects of other salinization sources than seawater intrusion, thus providing a more holistic vulnerability assessment. Therefore, this modified version of the GALDIT method could be applied in more coastal aquifers across the Mediterranean that may be influenced by various salinity sources, contributing to more efficient management strategies for the quantitative and qualitative protection of coastal aquifers.
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