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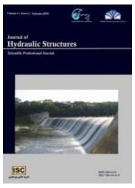

# Mapping Vulnerability of aquifer to saltwater intrusion using fuzzy membership function

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## Abstract

Groundwater is one of the most important sources of drinking, industrial, and agricultural water in arid and semi-arid regions, where the occurrence of droughts, rapid population growth, and the corresponding increase in water demand threaten groundwater resources. Over-exploitation and mismanagement of groundwater resources result in environmental problems such as subsidence and saltwater intrusion in coastal aquifers. The risk of saltwater intrusion threatens the Urmia aquifer due to the proximity of the aquifer to Lake Urmia and severe groundwater decline. This study evaluates the vulnerability of saltwater intrusion by the GALDIT framework. The results show the conservative vulnerability index with low efficiency, where vulnerable areas are limited to a narrow strip near the coastline. Fuzzy membership functions were employed within the GALDIT framework to increase efficiency. The results of the modified GALDIT resolve the weakness of presenting conservative results in the basic GALDIT framework.

**Keywords:** Saltwater Intrusion, GALDIT, Water Quality Index, Groundwater Level, Urmia Plain Aquifer

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## 1. Introduction

In many coastal aquifers, groundwater is considered the most important source of water supply for agriculture, drinking, and industry. In these areas, freshwater sources are subject to saltwater intrusion, which causes concerns for water security. Normally, the saltwater intrusion in coastal aquifers is due to high pumping rates and drops in the groundwater level, and this causes the degradation of the groundwater quality [1-3]. It is undeniable and necessary to deal with the problem of saltwater intrusion in coastal areas, especially in cases where we are faced with the rapid growth of the human population. Therefore, it is necessary to provide management and protection solutions. Assessing the vulnerability of groundwater and mapping areas prone to saltwater intrusion can be an effective help in this direction. Considering that decontamination of groundwater is a long process and often contamination is detected when decontamination of the aquifer becomes almost impossible, therefore preventing the contamination of groundwater systems is very important in the management of groundwater resources. One of the appropriate ways to prevent groundwater pollution is to identify the vulnerable areas of the aquifer. Based on the vulnerability study of an aquifer, the areas vulnerable to saltwater intrusion are mapped. The vulnerability index is a kind of relative, dimensionless, and unmeasurable characteristic and depends on the specifications of the aquifer and its geological and hydrogeological environment.

Groundwater vulnerability assessment should be based on scientific, accurate, and objective evidence. Different methods were introduced to assess vulnerability with high accuracy. In general, simulation, statistical, indexing and overlay (I/O) methods are used to assess the vulnerability of groundwater in many parts of the world. Simulation methods use mathematical models to estimate pollution, and their limitations are the need for very accurate data and the high sensitivity of the model to input data. The statistical method uses statistical techniques to determine the relationship between spatial variables and pollutants in groundwater, while minimize the error. The limitations of the method include the dependency of result on water quality observations, data accuracy, and accurate selection of spatial variables. The I/O method is widely used due to its simplicity, less need for data, and accurate description of vulnerability compared to other methods. In this method, the degree of vulnerability is calculated according to the indicators and the results are qualitative and relative [4]. Table 1 present a summary of recent studies conducted I/O methods to determine the vulnerability of coastal aquifers to saltwater intrusion. Based on the table, the basic and modified GALDIT frameworks were widely used [5] considering human and natural factors. Table 1 shows that the most important factors for assessing the vulnerability of coastal aquifers, including sea water rise, the height of the groundwater level at sea level [6-8], risks caused by climate change, overexploitation of aquifers [3,9] and pumping rate [10-11].

**Table 1. Summary of recent studies related to overlay/index (O/I) methods for mapping the vulnerability of coastal aquifers to saltwater intrusion**

| Researcher | Aquifer type | Validation factors | Key contributions |
|---|---|---|---|
| Lobo Ferreiraet al., (2005) | unconfined | – | • Climate change (for example, sea level rise) and overexploitation of aquifers have significant effects on saltwater intrusion . |
| Mahesha et al., (2011) | unconfined | $Cl^-/HCO_3^-$ | • The GALDIT framework for assessing the vulnerability of coastal aquifers to saltwater intrusion due to sea level rise is quite effective and reasonable . |
| Sophiya and Syed (2013) | unconfined | $Cl^-$ | • Temporal changes in the effective parameters in the intrusion of seawater in the aquifer are necessary . |
| Kura et al., (2015) | unconfined | $NO_3^-$ | • A very strong negative correlation has been observed between GALDIT and groundwater resistance (r=-0.86). |
| Pedreira et al., (2015) | unconfined | $Cl^-,NO_3^-$ | • The parameter of the height of the groundwater level above the sea level is a very important factor for evaluating the vulnerability of the aquifer to saltwater intrusion . |
| Recinos et al., (2015) | unconfined | $Cl^-$ | • The height of the groundwater above the sea level and the impact of saltwater intrusion are important parameters in the vulnerability of the aquifer . |
| Bouderbala et al., (2016) | unconfined | WQI | • GALDIT does not include the impact of pumping wells . |
| Najib et al., (2016) | unconfined | Pumping rate | • The obtained vulnerability mapping corresponds to the pumping rate . |
| Gorgji and Moghadam (2016) | unconfined | TDS | • In case of data limitations, the pumping rate can replace the distance of the water level from the sea level . |
| Klassen and Allen (2017) | unconfined | EC | • It is necessary to use the chemical indicators of underground water to accurately identify vulnerable areas to saltwater intrusion . |
| Allouche et al., (2017) | unconfined | $NO_3^-$ and Specific resistance of groundwater | • Land use parameter was added to GALDIT parameters.<br>• A negative correlation has been observed between GALDIT and the specific resistance of groundwater (r=-0.61). |
| Motevalli et al., (2018) | unconfined, confined and leaky | EC ، TDS and SAR | • A high correlation was observed between GALDIT output mapping (mean r = 0.73) and hydrogeochemical index factors .<br>• The depth of groundwater and the reduction of the level of groundwater were identified as the most important factors . |

This study employs the vulnerability assessment of saltwater intrusion in the Urmia aquifer using the GALDIT framework. To reduce the impact of expert judgment on the allocation of recommended rates, fuzzy membership functions were incorporated. Also, the time-varying parameters of this framework were prepared in different years and its effect on the GALDIT index were evaluated.

## 2. Methodology

### 2.1.The GALDIT Framework

GALDIT is a vulnerability indexing framework for saltwater intrusion that includes two parts assigning weight and rate values to the incorporated layers, which was developed by Chachadi and Lobo-Ferreira [18]. The GALDIT framework is based on the hydrogeological (water depth, aquifer thickness), physical (distance from the coast), hydrodynamic (hydraulic conductivity), and hydrochemical (sea intrusion effect) characteristics of the aquifer. In other words, GALDIT uses relatively simple layers with data that are easily collected to quantify the saltwater intrusion vulnerability index [18].

The word GALDIT is an acronym that stands for six incorporated layers used to evaluate the vulnerability index of saltwater intrusion. These layers include (G) Groundwater occurrence (type of aquifer: unconfined, confined, and leaky), (A) Aquifer hydraulic conductivity, (L) height of groundwater Level, (D) Distance from the shore, (I) Impact of existing saltwater intrusion status, and (T) aquifer Thickness. In this system, the first step involves assigning weight and rate values for each layer. The weight assigned to each layer shows its importance compared to others in the saltwater intrusion process. After preparing layers related to parameters using geographic information system processing, weights recommended by Chachadi and Lobo-Ferreira are applied to the corresponding layer. These weights are presented in Table 2 [18]. The ranking of the layers is also applied using dimensionless numbers ranging from 2.5 to 10 (2.5, 5, 7.5, and 10), according to the recommendations of Chachadi and Lobo-Ferreira [18]. The most important layer is assigned a weight of 4, while the least important parameter is assigned a weight of 1. The highest rate value indicates the highest vulnerability index, while the lowest rate value indicates the lowest vulnerability index. Finally, the decision criterion is the weighted sum of the rates of the incorporated layers.

**Table 2. Rate (left numerical column) and weight (bottom row) values for GALDIT layers**

| | | Groundwater occurrence (G) | Aquifer hydraulic conductivity (A) | height of groundwater Level (L) | Distance from the shore (D) | Impact of existing saltwater intrusion status (I) | aquifer Thickness (T) |
|---|---|---|---|---|---|---|---|
| Rate | 10 | confined | >40 | <1 | <500 | >2 | >10 |
| | 7.5 | unconfined | 10-40 | 1-1.5 | 500-750 | 1.5-2 | 7.5-10 |
| | 5 | leaky | 5-10 | 1.5-2 | 750-1000 | 1-1.5 | 5-7.5 |
| | 2.5 | Bounded aquifer (limited to hydrogeological boundaries) | <5 | >2 | >1000 | <1 | <5 |
| Weight | | 1 | 3 | 4 | 4 | 1 | 2 |

GALDIT index (GI) is calculated as follows:

$$GI = G_r G_w + A_r A_w + L_r L_w + D_r D_w + I_r I_w + T_r T_w \quad (1)$$

where the subscripts *r* and *w* indicate the rates and weights of layers, which are applied as per the values in Table 2. The minimum and maximum GALDIT index can be calculated according to Equation 1 and Table 2. The vulnerability of the coastal area to saltwater intrusion is estimated based on the value of the GALDIT index. The lower the value of the GALDIT index causes the lower the vulnerability of the area to saltwater intrusion. When the GALDIT index is calculated, it becomes possible to classify the desired area into several classes.

## 2.2.The Study Area

The study area is situated in Urmia Plain, which is located in West Azerbaijan province in the northwest of Iran. The plain covers an approximate area of 1000 km$^2$ and encompasses the alluvial aquifer. It also includes the main river basins, such as Shahrchay, Nazlochay, Rozechay, and Baranduzchay. The rivers originate in the Mor Daghlar mountain range, along the borders between Turkey and Iran. These rivers are fed by the Saru, Silvana, Moana, and Ziveh mountains. The general channel of surface water flow in Urmia Plain flows from west to east and towards Lake Urmia. The plain has an average height of 1320 meters above sea level, according to the Digital Elevation Model (DEM) of the Landsat satellite, as shown in Figure 1.

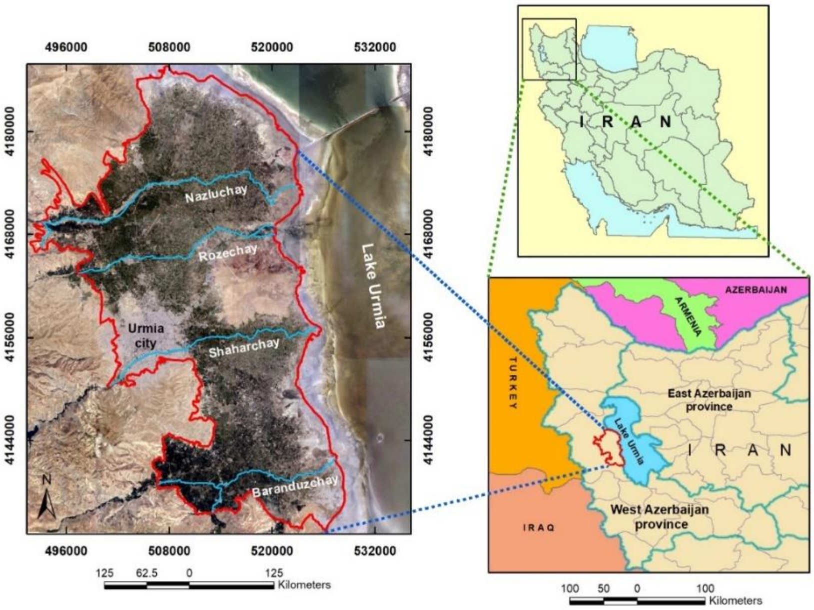

**Figure 1. Location map of the study area**

The quality and quantity of groundwater have a direct impact on the economic and livelihood issues of the people living in the Urmia Plain. In general, in the aquifers on the edge of Lake Urmia, extensive dam construction has hurt surface water resources. Currently, the surface and groundwater resources of Urmia Plain are facing damages due to incorrect planning, including a sharp decrease in the groundwater level, which was also reported in the survey conducted by Amirataee and Zeinalzadeh (2016) [19]. Our investigations show the monthly changes in the water level of Lake Urmia is 2.7 cm/month; and the monthly changes in the water level is 1.8 cm/month in a period of 16 years (2009-2015). Also, the correlation coefficient between the level of the lake and the level of the groundwater level was calculated as 0.71. The calculated value for the correlation coefficient indicates the mutual relationship between the lake and the aquifer.

## 3. Results and Discussion

### 3.1. Assessing the Vulnerability of Saltwater Intrusion using the GALDIT Framework

Figure 2 displays the layers that contributed to the GALDIT framework in the Urmia Plain aquifer. The first layer of GALDIT, which represents the Groundwater occurrence (G), is shown in Figure 3(a). Since the Urmia plain aquifer is an unconfined aquifer, the rate of this layer has a constant value of 7.5 and does not cause any spatial changes in the calculation of the GALDIT index. The second layer, Aquifer hydraulic conductivity (A), is presented in Figure 2(b) and is based on the result of the pumping test. The figure indicates that in the southeastern parts of the plain near the coast, its value is in the medium range, which can increase the vulnerability index of saltwater intrusion. Although the outskirts of Urmia city and west of the plain have relatively high hydraulic conductivity, their distance from the coastline is expected to prevent significant effects in increasing the vulnerability of saltwater intrusion.

The layer corresponding to height of groundwater Level (L) is shown in Figure 2(c). This layer was calculated using the data of groundwater level and sea level in August 2009 and prepared using the kriging interpolation technique. The figure indicates that this layer decreases as it approaches the coastline, which increases the vulnerability to saltwater intrusion. It should be noted that this layer is one of the dynamic parameters of GALDIT that changes over time. Therefore, the spatial distribution of this layer was prepared in different years to investigate the effect of temporal changes on the GALDIT index, which are discussed subsequently.

Figure 2(d) shows the spatial distribution of the layer related to Distance from the shore (D), which was calculated using the Euclidean distance tool in ArcMap software. The Euclidean distance decreases by approaching the coastline, which can increase the vulnerability to saltwater intrusion. Spatial distribution of the Impact of existing saltwater intrusion status (I) was calculated using the qualitative data of the ratio of chloride ions to the total of bicarbonate and carbonate ions in August 2009 and using the kriging interpolation technique, The results are shown in Figure 2(e). According to this figure, it can be seen that the value of this index is high in the eastern part of the plain near the coastline, which can increase the vulnerability to saltwater intrusion. It should be noted that this layer, like the L layer, is one of the dynamic layers of GALDIT, and its temporal changes will be evaluated in the following. The aquifer Thickness (T) as the last layer contributed in the GALDIT framework is extracted from the results of the geoelectrical profiles of the geophysical test and after interpolation with the kriging method, it is shown in Figure 2(f).

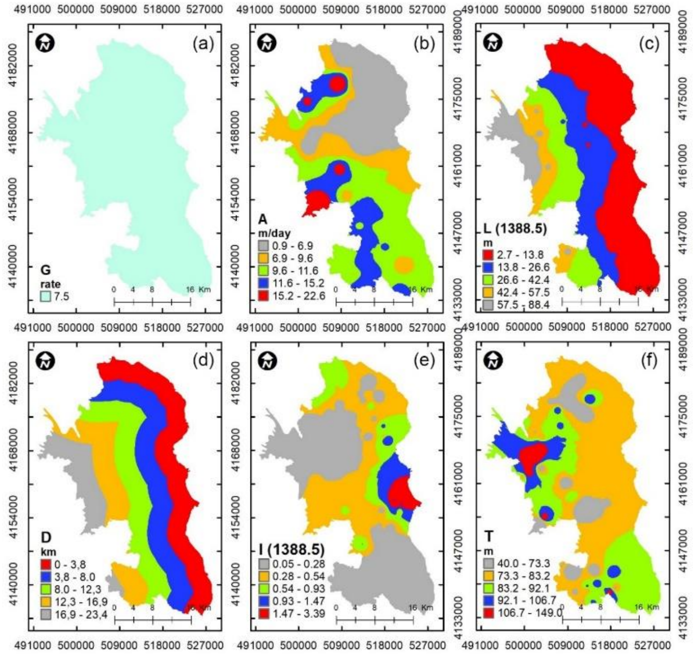

**Figure 2. The GALDIT layers: (a) Groundwater occurrence, (b) Aquifer hydraulic conductivity, (c) height of groundwater Level, (d) Distance from the shore, (r) Impact of existing saltwater intrusion status and (g) aquifer Thickness**

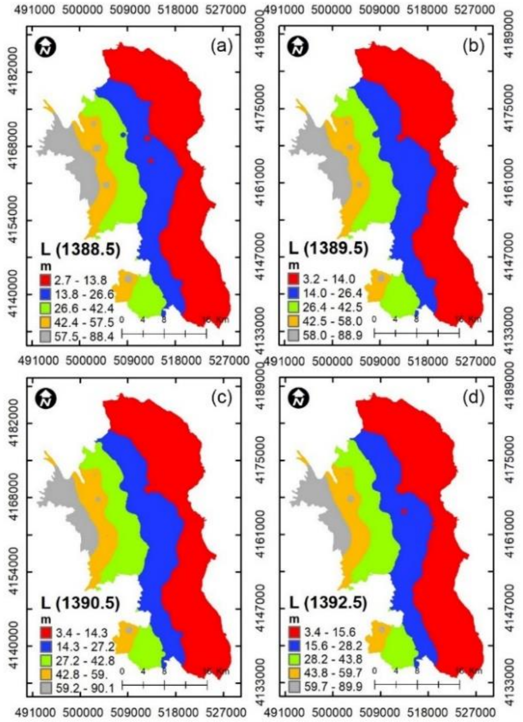

**Figure 3. Temporal changes of the layer L of the GALDIT framework: (a) August 2009, (b) August 2010, (c) August 2011, (d) August 2012**

Figure 3 shows the spatial distribution of the layer of height of groundwater Level (L) in August 2009, 2010, 2011, and 2012. According to the figure, it can be seen that despite the changes in L values, the spatial pattern does not change significantly. Therefore, it is expected that the temporal changes of this parameter will not have much effect on the vulnerability of saltwater intrusion. It should be noted that the selection of data in the above years was selected according to the accessibility of the data.

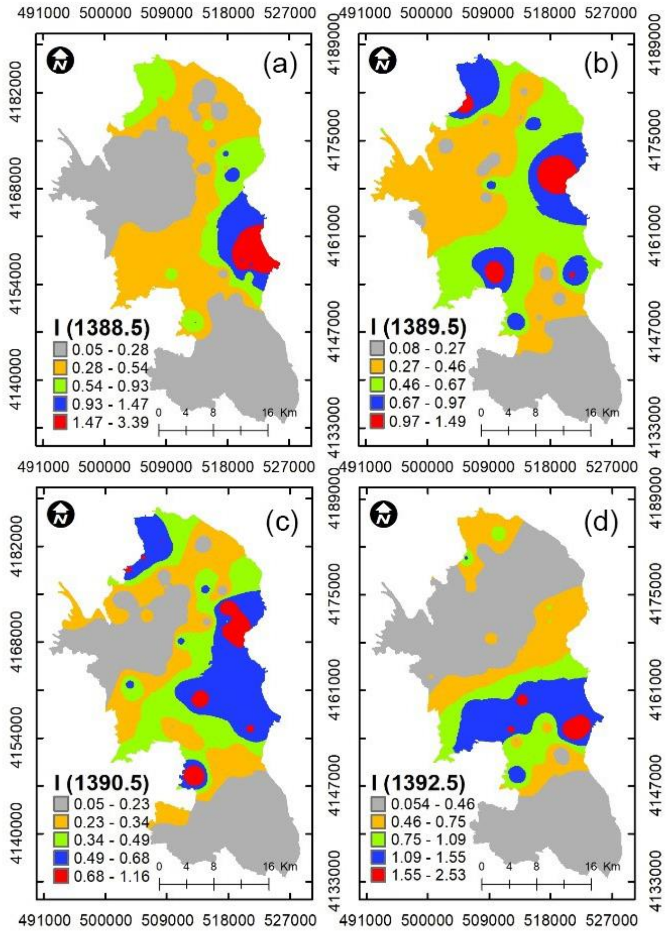

**Figure 4. Time changes of parameter I of the GALDIT framework: (a) August 2009, (b) August 2010, (c) August 2011, (d) August 2012**

Figure 4 shows the spatial distribution of the influence layer of the Impact of existing saltwater intrusion status (I) in August 2009, 2010, 2011, and 2012. According to the figure, it can be seen that the pattern of spatial changes of this parameter in the aforementioned years is remarkable. But despite time changes, high values for this layer are observed in the eastern part of the plain near the coastline, which can intensify the vulnerability of saltwater intrusion in these areas.

## 3.2.The results of Saltwater Intrusion Vulnerability using Basic GALDIT

After preparing the contributed layers in the GALDIT framework, considering that each of the layers has a different unit (dimension) and interval of changes compared to each other, these layers using the recommended rate values in Table 2 were classified, then weighted overlay analysis was performed using the weights presented in the table. The results of this analysis, which shows the GALDIT index in the vulnerability of saltwater intrusion, are presented in Figure 5. It should be noted that considering the temporal changes of L and I parameters, the vulnerability results for the years 2009, 2010, 2011, and 2012 are shown separately in this figure. It can be seen carefully in this figure that in a very narrow band near the coastline, the vulnerability of saltwater intrusion is high. In other words, GALDIT has presented very conservative results, so in the areas outside this band with a very small area, the vulnerability of the aquifer is in the low to medium range, which according to the characteristics of the study area and the researchers' knowledge of the plain Urmia does not seem logical.

## 3.3.Vulnerability Results using the Modified GALDIT

The reason for providing conservative results by the Basic GALDIT framework is the existence of pre-recommended rates by expert judgment, which causes the classification of some layers in one or two classes. It is worth mentioning that the classification of layers in one or two classes reduces the effect of that layer on the final result. This section aims to reduce the influence of expert judgment in the classification of layers by using fuzzy membership functions and taking into account the characteristics of the studied area. For this purpose, fuzzy membership functions were used to normalize GALDIT layers. Considering that GAIT parameters are directly related to saltwater intrusion, the values of these layers are normalized from the maximum value to the minimum value to 1 to 0 respectively. While L and D parameters are inversely related to saltwater intrusion, the values of these layers are normalized from the maximum value to the minimum value to 0 to 1, respectively. The normalization of layers using fuzzy membership functions causes the range of changes of all layers to change between zero and one, and the layers become dimensionless. Based on this process, an arbitrary pixel in a layer takes a value between 0 and 1 according to the characteristics of the same layer. While the equivalent of this process is in the Basic GALDIT framework, classification is based on recommended rates, and the number of classes is determined based on expert judgments.

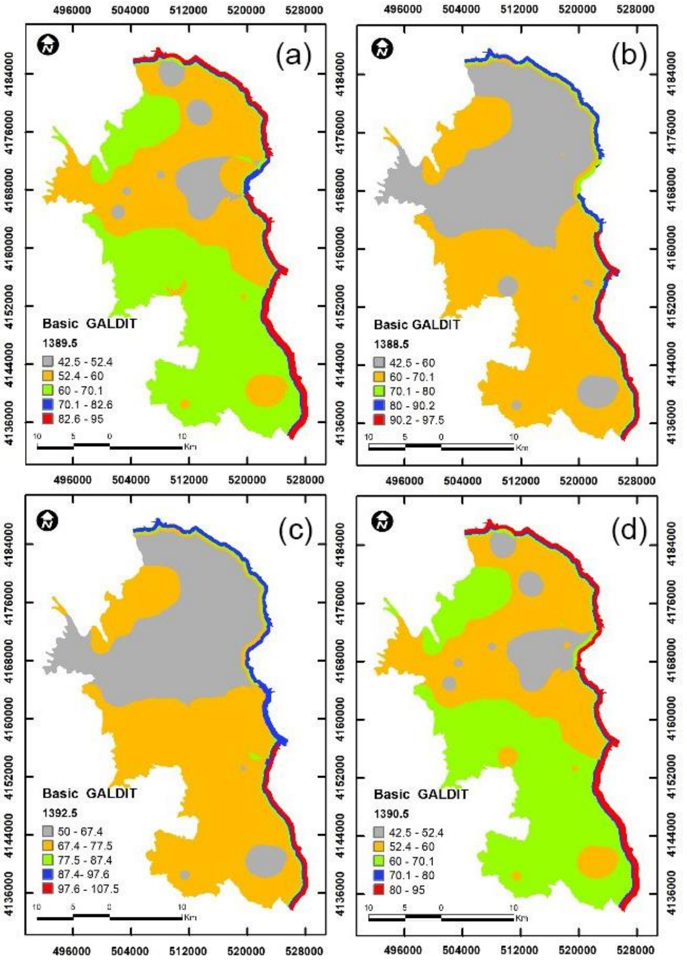

**Figure 5. Spatial distribution of vulnerability index based on Basic GALDIT framework and time changes: (a) August 2009, (b) August 2010, (c) August 2011, (d) August 2012**

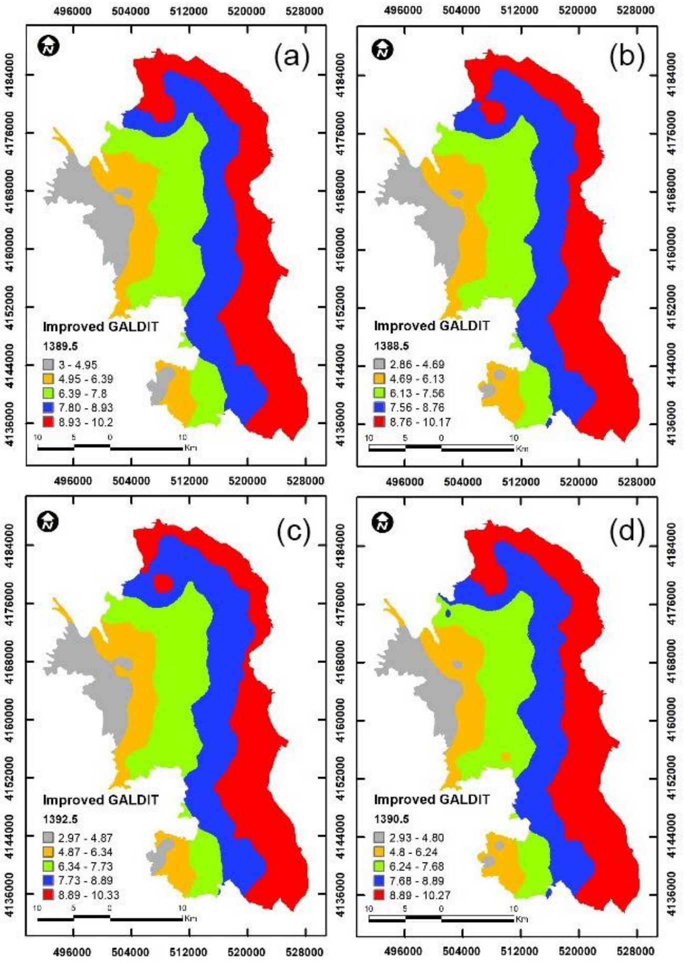

**Figure 6. Spatial distribution of vulnerability index based on modified GALDIT framework and time changes: (a) August 2009, (b) August 2010, (c) August 2011, (d) August 2012**

The revised GALDIT index was calculated using the relative importance of the layers by the weights presented in Table 2 and the normalized layers by the fuzzy membership functions and its results for August 2009, 2010, 2011, and 2012 are shown in Fig. 6. Considering this figure, it can be seen that the temporal changes of GALDIT dynamic layers (L and I layers) do not have a significant effect on the final result of vulnerability. Of course, this issue may not be true in other aquifers. It can also be seen that the vulnerability index increases as you get closer to the coastline. A comparison of Figure 6 and Figure 6 shows that, unlike the Basic GALDIT framework, the modified method did not provide conservative results and a significant area near the coastline has a high vulnerability index.

## 4. Conclusion

Fresh water stored in coastal aquifers is exposed to salinity due to its proximity to saltwater, the high demand for water, and the high population density. The salinity of groundwater sources is considered one of the main sources of pollution that threatens groundwater sources. Therefore, to protect groundwater resources in coastal areas, the intrusion of saltwater should be prevented and the management of these aquifers should be done effectively. Assessing the vulnerability of coastal aquifers to saltwater intrusion is considered a tool to prevent groundwater salinization. The GALDIT framework has been widely used to assess the vulnerability of saltwater intrusion in coastal aquifers. The GALDIT framework is an indexing technique that includes the following six layers, which include the type of aquifer (G), hydraulic conductivity of the aquifer (A), groundwater level above sea level (L), distance from the coast (D), impact the existing state of seawater (I) and the thickness of the aquifer (T).

In this study, the vulnerability of saltwater intrusion in the Urmia Plain aquifer has been evaluated. For this purpose, the GALDIT framework, which is one of the common methods for evaluating saltwater intrusion in coastal aquifers, has been used. The results showed that the GALDIT framework provides conservative results. So the vulnerability is high in narrow areas near the coastline and most of the plain (about 90%) is in the range of low to medium vulnerability, which is not compatible with the reality of the plain. Therefore, based on the evaluations, it was determined that the reason for the presentation of conservative results by the GALDIT framework is the existence of pre-defined rates. To resolve this limitation, instead of assigning these rates, fuzzy membership functions that normalize the layers between zero and one have been used.

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