environmental sciences proceedings

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Proceeding Paper

Seawater Intrusion Vulnerability Assessment Using the GALDIT and the Modified GALDIT–AHP Methods: Application in the Coastal Almyros Aquifer, Thessaly, Greece †

Sibianka Lepuri [1,*], Athanasios Loukas [1] and Aikaterini Lyra [2]

[1] Laboratory of Hydraulic Works and Environmental Management, School of Rural and Surveying Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; agloukas@topo.auth.gr
[2] Laboratory of Hydrology and Aquatic Systems Analysis, Department of Civil Engineering, School of Engineering, University of Thessaly, 38334 Volos, Greece; lyrakater@gmail.com
* Correspondence: sibiankalepuri@gmail.com
† Presented at the 7th International Electronic Conference on Water Sciences, 15–30 March 2023; Available online: https://ecws-7.sciforum.net.

Abstract: In the rural and coastal Almyros basin in Magnesia, Greece, the objective of the current study is the assessment of aquifer vulnerability to seawater intrusion using the GALDIT approach. The Almyros aquifer system's quality and quantity have declined as a result of unsustainable groundwater abstraction for irrigation. The Analytical Hierarchy Process (AHP) of Multicriteria Analysis has been used for the modification of the GALDIT index based on the statistics of experts' responses to questionnaires on the influence of hydrological, hydrogeological, and other parameters [1]. For all methodologies and time periods, the aquifer's coastline section had high susceptibility levels whereas the northeast and southeast had lower values. The most vulnerable area of the aquifer changes over the various time periods of analysis.

Keywords: groundwater; seawater intrusion; GALDIT; vulnerability index; Analytical Hierarchy Process; Almyros

Citation: Lepuri, S.; Loukas, A.; Lyra, A. Seawater Intrusion Vulnerability Assessment Using the GALDIT and the Modified GALDIT–AHP Methods: Application in the Coastal Almyros Aquifer, Thessaly, Greece. *Environ. Sci. Proc.* **2023**, *5*, x. https://doi.org/10.3390/xxxxx

Academic Editor(s):

Published: 15 March 2023

1. Introduction

In the study area, no previous studies have been carried out to assess the vulnerability of the aquifer to seawater intrusion. The over-pumping of water reserves to meet irrigation needs has degraded the quality and quantity of water in the Almyros aquifer. The assessment of vulnerability aims at better management of water resources in the area and protection from further degradation of the Almyros aquifer system [1]. The Almyros basin, which is located at the southernmost edge of the Thessalian plain, is a component of the single Almyros-Pagasitikos basin. The study area's aquifer covers 293 km^2 and has an average elevation of around 108 m and slope of about 5.56%. The Almyros basin experiences a semi-arid Mediterranean environment with 500 mm of annual rainfall on average and an average yearly temperature of 16.5 °C [2]. Five categories have been used to group the most significant geological components of the Almyros aquifer: clay (Neogene), clay-gravel-sand (Neogene), sand (Quaternary), clay-sand (Neogene), and limestone [3]. Following the shift in topographic elevation, the coastal region of the Almyros basin is composed of sandy permeability materials and clay lenses towards the western half of the aquifer. The aquifer's hydrogeological zones are made up of semi-permeable Neogene formations and permeable Quaternary formations [4]. With a geographical average value of 2.3 m per day, hydraulic conductivity values range from 0.1 to 18.7 m per day. In this work, the weights of the parameters are provided using the standard/typical GALDIT method, and the weights are estimated using the Analytical Hierarchy Process (AHP) from the responses of 15 experts, using the GALDIT-AHP method, over three time periods in the Almyros Basin aquifer. The results on seawater intrusion vulnerability are compared and discussed.

2. Materials and Methods

2.1. Method GALDIT

The GALDIT vulnerability index approach, which was put forth by Lobo-Ferreira and associates [4], determines how vulnerable coastal aquifers are to the salt wedge. The following phrases are abbreviated as the GALDIT method: (a) Groundwater occurrence, (b) aquifer hydraulic conductivity, (c) depth to groundwater (level above the sea), (c) distance from the shore to the beach, (d) effects of present seawater intrusion, and (e) aquifer thickness are the six factors that must be considered. The three components of the procedure are the calibration of the parameters, the classes of the parameters, and the weights of the parameters. The method was first applied to the Bardez aquifer, Goa (India) [5]. The vulnerability assessment index is calculated from the mathematical type:

$$GALDIT = \frac{\sum_{i=1}^{6}\{(W_i)R_i\}}{\sum_{i=1}^{6} W_i} \tag{1}$$

where, W_i = the weights of the parameters, R_i = the rating of the parameters. The value range of the index is 2.5–10. Indicators with higher values indicate greater exposure to seawater incursion, whereas those with lower values indicate less exposure.

2.2. AHP Method

Saaty first developed the Analytical Hierarchy Process (AHP) in the 1970s. Since then, it has proven to be a useful tool for creating and modeling scenarios with various, frequently at odds objectives. The method solves a problem in 6 stages [6] which are: (1) segmentation of the problem, (2) prioritization of objectives, criteria and sub-criteria and alternatives, (3) creation of the table of paired observations, (4) estimation of relevant parameters, (5) estimation of consistency, and finally, (6) general comparison of the method. The reliability of the method is based on the consistency ratio (CR). If CI/RI < 0.10, the degree of consistency is satisfactory, so little subjectivity, but if CI/RI is greater than 0.10, there may be major discrepancies and Analytic Hierarchy Method (AHP) conclusions may not be significant. In the context of this work, for each vulnerability method, the corresponding tables of pairwise tables were created and completed by 15 water resources experts including university professors, researchers and post-docs [1].

2.3. Sperman Rank Correlation

The Spearman correlation coefficient is named after Charles Spearman and is denoted by the Greek letter ϱ (*rho*) or rs. It is a non-parametric method, which is applied when the parametric conditions are not satisfied (i.e., normality and linearity, the range of observations and the existence of an iso-space scale). The magnitude of agreement is expressed by the sign and magnitude of the Spearman correlation statistic. The equation for calculating the Spearman correlation coefficient is as follows:

$$rho = \frac{6\sum \delta i^2}{\nu(\nu^2 - 1)} \tag{2}$$

where, ν is the number of pairs, and must n ≥ 4 and δi is the difference in order between the first and second measurements (pairs of measurements). The hypotheses tested when applying the Spearman correlation index are H0: ϱ = 0 (lack of correlation between observations), H1: ϱ = /0 existence of correlation between observations. A frequently used significance level is α = 0.05. That is, there is a 95% probability that each observed statistical difference is real and not due to chance [7].

3. Results and Discussion

3.1. Calculation of Vulnerability Index GALDIT and Modified GALDIT–AHP

The method was applied for all three study periods 1992–1997, 2004–2009 and 2010–2015. Therefore, parameters that do not remain constant per time period, such as the hydraulic load above sea level, the existing salinity condition and the aquifer thickness, were calculated for each period using GIS tools. The type of aquifer, based on the geological and hydraulic conditions prevailing in the study area, was considered alluvial/unconfined. In the Almyros basin, as already mentioned, hydraulic conductivity information of the unsaturated zone is provided by the European Soil Data Center (ESDAC) [8]. For the study area hydraulic conductivity varies between 0.05–18,701 m/day or 2.29 m/day on average. For the period 1992–1997, the hydraulic head above sea level was an average of 65.44 m and a maximum value of 217.59 m, in the period 2004–2009 it was 66.85 m and a maximum value of 218. In the period of 2010–2015 was 66.40 m and a maximum value of 217.39 m. The very low values are located NE–SE of the Almyros basin, near the basin's coastline region, while the high values of the hydraulic load increase towards the center of the aquifer, moving in the direction of the Holorema stream. The highest concentrations of chlorides measured at the measurement sites are shown on the SE side of the basin, in the Xirorema and Platanorema sub-basins. The average thickness for the aquifer media is 29 m but is not constant in all locations in the Almyros basin. The Almyros basin's map and the study area is depicted in the Figure 1.

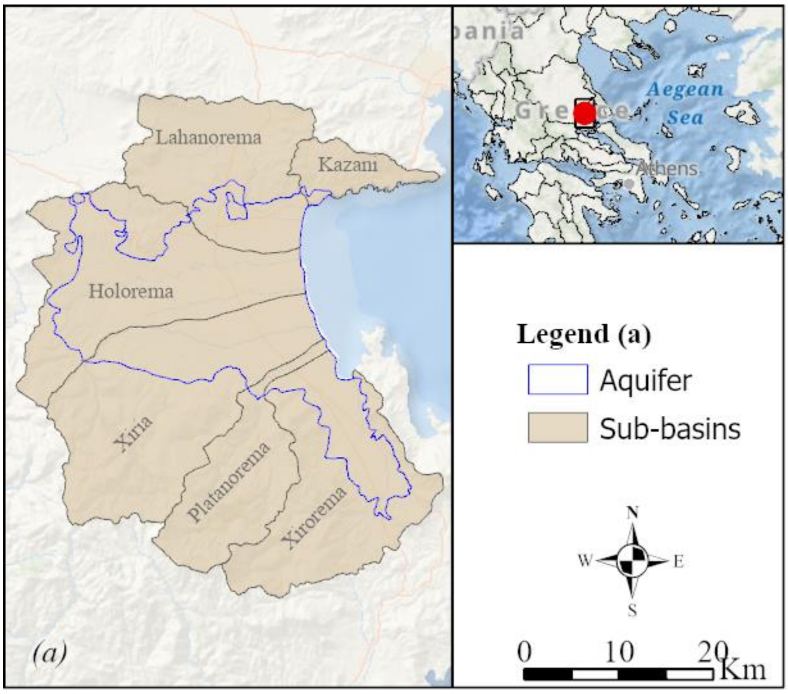

Figure 1. Map of the Almyros basin including the aquifer and the sub-basins.

The weights of the parameters for the statistical indicators median, average, and mode, as determined by the statistical analysis of the 15 experts' responses, were taken from the GALDIT-AHP method's study of the data. The consistency ratio (CR) for each statistical indicator is less than 10%. Specifically, the consistency ratio of the AHP Median, AHP Average and AHP Mode is 2%, 0.43% and 8.8%, respectively. The weights of the parameters for each statistical index are presented in the Table 1.

Table 1. The weights of each parameter for the GALDIT method and the modified GALDIT-AHP method.

Parameters	Typical	AHP Median	AHP Average	AHP Mode
Groundwater occurrence	0.060	0.276	0.282	0.235
Aquifer hydraulic conductivity	0.200	0.263	0.246	0.235
Level above the sea	0.266	0.190	0.170	0.214
Distance from the shore	0.266	0.118	0.146	0.127
Impact of existing seawater intrusion	0.060	0.081	0.086	0.099
Thickness of the aquifer	0.133	0.072	0.070	0.090

The GALDIT method assigns the greatest weights to the parameters of distance from the coast (D) and hydraulic load above the sea (L). The modified GALDIT-AHP assigns the greatest weights to the parameters of the groundwater occurrence (G) and the aquifer hydraulic conductivity (A). The resulted maps for all the methods for the evaluated time periods are presented in Figure 2.

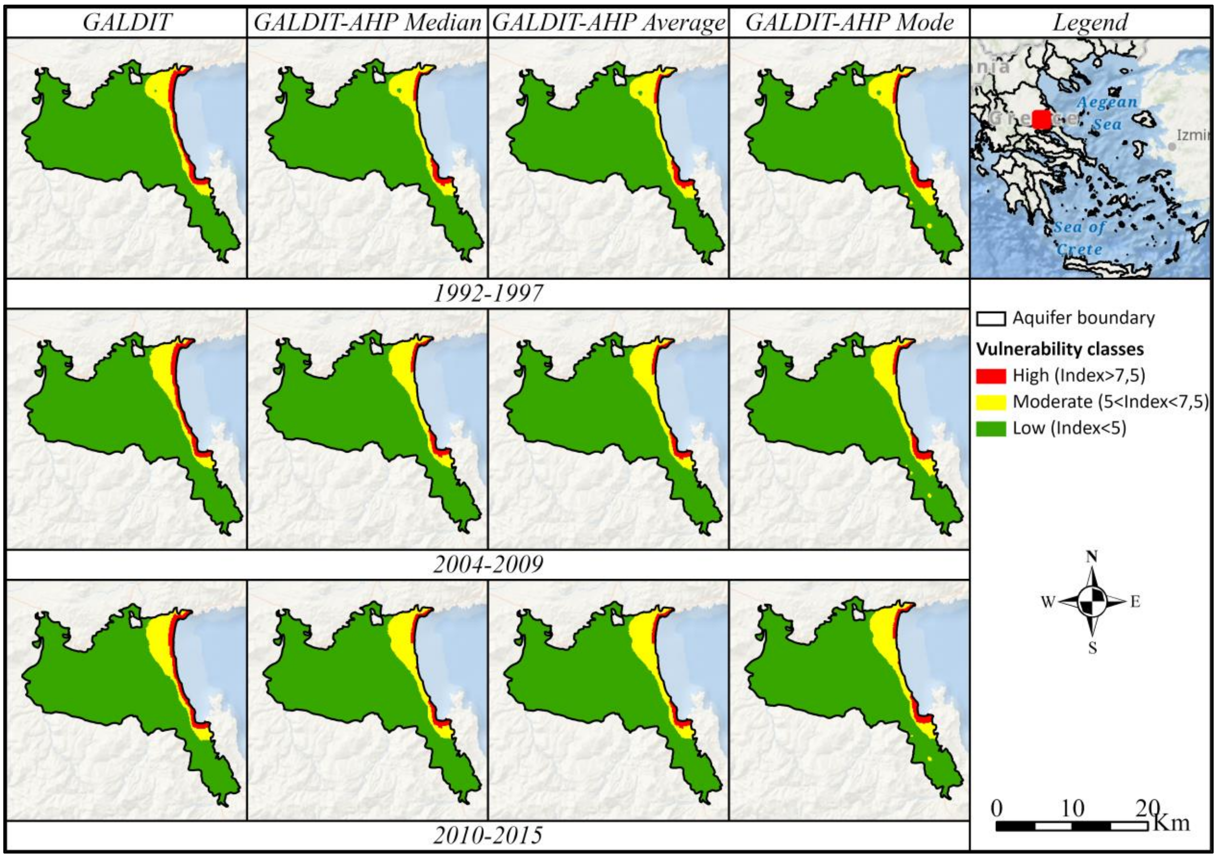

Figure 2. Vulnerability maps of Almyros aquifer with the methods of GALDIT and modified GALDIT–AHP for the periods 1992–1997, 2004–2009, 2010–2015.

The areas in which a greater extent of high and medium vulnerability is observed are in the Kazani, Lahanorema and Xirorema sub-basins. In the period 1992–1997 the total percentage of high vulnerability among the indexes covers 1.98% to 3.5% of the aquifer or an area of 5.7 km^2 to 10 km^2. The lowest overall percentage is estimated by the GALDIT–AHP Average and Median indices. Average vulnerability across indices ranges from 7.2% to 8.7% or an area of 20.7 km^2 to 24.8 km^2. The lowest percentage of average vulnerability was estimated with the weights of the GALDIT index, while the highest percentage of average vulnerability was estimated with the weights of the AHP Mode index. Low vulnerability ranges from 89.17% to 89.92% or an area of 255 km^2 to 258 km^2. In the period

2004–2009 the total percentage of high vulnerability among the indices covers 1.94% to 3.6% of the aquifer or an area of 5.6 km^2 to 10.3 km^2. The lowest overall rate is estimated by the GALDIT–AHP Average and Median indices. Average vulnerability across indices ranges from 8.1% to 9.6% or an area of 23.3 km^2 to 27.6 km^2. The lowest percentage of average vulnerability was estimated with the weights of the GALDIT index, while the highest percentage of average vulnerability was estimated with the weights of the AHP Mode index. Low-vulnerability ranges from 88.2% to 88.8% or an area of 253 km^2 to 255 km^2. In the period 2010–2015 the total percentage of high vulnerability among the indices covers 2% to 3.6% of the aquifer or an area of 5.9 km^2 to 10.2 km^2. The lowest overall percentage is estimated by the GALDIT–AHP Average and Median indices. Average vulnerability across indices ranges from 9.1% to 10.4% or an area of 26.2 km^2 to 30 km^2. The lowest percentage of average vulnerability was estimated with the weights of the GALDIT index, while the highest percentage of average vulnerability was estimated with the weights of the AHP Mode index. Low vulnerability ranges from 87.3% to 87.7% or an area of 251 km^2 to 252 km^2. Summarized statistics of the evaluation period (1992–2015) are presented in Table 2.

Table 2. Percentage (%) of the Almyros Aquifer under various classes of vulnerability (%) with the typical GALDIT and GALDIT–AHP methods for the period 1992–2015.

Vulnerability Classes	Typical	AHP Median	AHP Average	AHP Mode
High	3.54%	1.99%	1.99%	2.20%
Moderate	8.16%	9.23%	9.21%	9.57%
Low	88.27%	88.70%	88.80%	88.24%

3.2. Sperman Rank Correlation

To test the correlation between salinity concentrations (ppt) and GALDIT seawater intrusion index values for all three time periods, the Spearman correlation coefficient was used. Salinity values and the GALDIT vulnerability index were extracted from the sampling sites using the Extract multi values to points tool. The Spearman correlation test was then performed using the SPSS statistical software. Then, using the SPSS statistical package, the Spearman correlation test followed. Summarized statistics of the evaluation period are presented in Table 3.

Table 3. Spearman rank correlation between salinity concentrations and vulnerability indices GALDIT and modified GALDIT–AHP.

Vulnerability Indices	1992–1997	2004–2009	2010–2015
GALDIT	0.44	0.45	0.45
AHP Median	0.43	0.44	0.44
AHP Average	0.44	0.44	0.43
AHP Mode	0.43	0.45	0.46

The significance (p) value of the correlations is less than 0.05 thus the statistical difference is real and not due to chance. Correlation coefficients range from *rho* = 0.43 to 0.46 per study period.

4. Conclusions

In all the study periods (1992–1997, 2004–2009 and 2010–2015) a gradual increase of high and medium vulnerability values (0.5–2%) was observed, a fact due to changing parameters such as the hydraulic load above sea level, the existing salinity condition and the aquifer thickness which change with time. For the GALDIT index, the standard/typical weights, the weights of the AHP Median and AHP Average statistical indicators showed in all study periods a similar overall rate of high vulnerability with a difference of 0.5–1%. Additionally, there are marginal differences in the correlation coefficients between the GALDIT indices and the observed data, with the GALDIT index generated using standard weights displaying the highest connection throughout all research periods. As a result, when compared to the other indices, the standard weights of the GALDIT index slightly better represent the vulnerability assessment both spatially and statistically. The GALDIT method assigns the greatest weights to the parameter of distance from the coast (D) and to the parameter of hydraulic load above the sea (L).

Author Contributions: Conceptualization, methodology, supervision, writing-review and editing, A.L.; methodology, software, data curation, writing—original draft preparation, writing—review and editing, S.L.; writing—review and editing, A.L. All authors have read and agreed to the published version of the manuscript.

Informed Consent Statement: Not applicable.

Acknowledgments: This research was carried out in the framework of the Master thesis of S. Lepuri, Laboratory of Hydraulic Works and Environmental Management, School of Rural and Surveying Engineering, Aristotle University of Thessaloniki.

Conflicts of Interest: The authors declare no conflict of interest.

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