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A modified GALDIT-NUTS index to assess Favignana Island aquifer vulnerability

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Abstract

The present research aims to assess the role of geogenic and anthropogenic activities in coastal aquifer vulnerability using a modified index. To achieve the objective of the current research, a GIS-based GALDIT-NUTS index has been developed for aquifer vulnerability assessment on Favignana Island, Italy. The GALDIT-NUTS index has been developed by expanding the GALDIT index using three significant parameters of the DRASTIC index and adding the landuse of the area. The GALDITS-NUTS index and the different index weights were validated using a hierarchical analytical process, vulnerability rating (obtained by this application), and field observed aquifer electrical conductivity data. The GALDIT-NUTS showed that approximately 66.4% of the study area was covered with high to maximum vulnerability zones and followed by medium vulnerability zones (32% of the study area). The present research outcome suggested that the GALDIT-NUTS index helps assess Island aquifer vulnerability because the index considers both human and seawater intrusion impacts.

Keywords Aquifer vulnerability, landuse impact; validation of index, coastal aquifer management; GIS

1. Introduction

Groundwater resources are a vital source of utilization for different purposes, such as domestic, industrial and irrigation in coastal areas and island nations. Almost 2.4 billion (~40%) people of the globe live within the 100 km distance from the coast (UN, 2017) and primarily depend on groundwater for different uses. However, groundwater declining in terms of quantity and quality is a crucial challenge to coastal and island society due to several anthropogenic, geogenic and climatic factors (Vengosh and Rosenthal, 1994; Church et al., 2007; Aeshbach-Hertig and Gleeson 2012; Leung et al., 2012; Bailey et al., 2015; Huang et al., 2013; Baena-Ruiz et al., 2020; Micallef et al., 2020). Groundwater overexploitation, extensive agriculture and other human activities are the main factors for coastal and island aquifer salinization and degradation (Re et al., 2014; Chatton et al., 2016; Allouche et al., 2017; Kazakis et al., 2006, 2017; Abu-alnaeem et al., 2018; Busico et al., 2018; Kanagaraj et al., 2018; Tiwari et al., 2019). Aquifer salinization in coastal zones can reduce freshwater availability and cause an adverse effect on the health of ecosystems and human beings

(Patel and Shah, 2008). Therefore, sustainable coastal aquifer management plans are required to meet the present and future freshwater necessities (Kazakis et al., 2018)

Researchers have developed several indices from across the globe to assess the aquifer vulnerability situation, such as DRASTIC (Aller et al., 1987), GOD (Foster, 1987), AVI (Van Stempoort et al., 1993); SINTACS (Civita and De Maio, 1997), EPIK (Doerfliger and Zwahlen, 1998), PI (Goldscheider et al., 2000), GALDIT (Chachadi and Lobo-Ferreira, 2001) etc. These indices were developed according to specific conditions and based on different datasets (Kardan Moghaddam et al., 2017) and played a significant role in water resources management. On the other hand, a geographic information system (GIS) is a powerful software to identify the most vulnerable areas. It is used to manage, elaborate and create geographical data, as well as play a vital role in the different vulnerability indices to develop the thematic maps of highly vulnerable zones (Panagopoulos et al., 2006; Saidi et al., 2014; Ghosh et al., 2015; Fetisova et al., 2016; Tiwari et al., 2021). GIS plays a significant role in the development of methods or indices to assess the groundwater vulnerability to pollution, mapping the risk of seawater intrusion and helping in sustainable management of water resources (Saidi et al., 2013; Kaliraj et al., 2015; Allouche et al., 2015; Pacheco et al., 2015; Tiwari et al., 2016; Satishkumar et al., 2016; Barbulescu et al., 2020; Baena-Ruiz, and Pulido-Velazquez, 2021).

Lobo-Ferreira et al., 2005 has proposed a definition for groundwater vulnerability to seawater intrusion in the coastal regions as "*the sensitivity of groundwater quality to an imposed groundwater pumping or sea-level rise or both in the coastal belt, which is determined by the intrinsic characteristics of the aquifer*". The GALDIT index is the most popular and reliable method to evaluate aquifer vulnerability in coastal regions. Recently, several researchers have used the GALDIT index to assess the groundwater vulnerability in the coastal areas (Kallioras et al., 2001; Cimino et al., 2008; Mahesha et al., 2011; Sophiya and Syed, 2013; Recinos et al., 2015; Kura et al., 2015; Bouderbala et al., 2016; Gontara et al., 2016; Benini et al., 2016; Kardan Moghaddam et al., 2017; Corman, 2017; Motevalli et al., 2018; Ayed et al., 2018; Seenipandi et al., 2019). Also, the GALDIT index has been used to assess the karstic coastal aquifer vulnerability of Mediterranean Sea region. For example, Zaarour (2017) used GALDIT index to determine the karstic coastal aquifer vulnerability of Ghadir in Central Lebanon. Mavriou et al. (2019) have also used GALDIT index to assess the vulnerability of karstic coastal aquifer of Rhodes Island, Greece. The studies show that GALDIT is applicable for karstic aquifer coastal vulnerability assessment. Besides, researchers have also used the DRASTIC index to assess the vulnerability of coastal aquifer (Kaliraj et al., 2015; Zghibi et al., 2016) because the DRASTIC index can be applied to all kind of aquifers (Kardan Moghaddam et al., 2017). Thus, both GALDIT and DRASTIC indices can significantly assess the vulnerability of the coastal aquifer of any region.

Researchers have modified the DRASTIC index modifying the significant parameters to improve the DRASTIC framework in agricultural, urban and industrial sectors (Fritch et al., 200; Neshat et al., 2014a; Sinha et al., 2016; Singha et al., 2019; Baena-Ruiz and Pulido-Velazquez, 2020). However, in some studies related to coastal areas also, the DRASTIC framework has been modified, for example, DRASTICSea (Javadi et al., 2020), M-DRASTIC (Khoshdooz-Masooleh et al., 2014), and IM-DRASTIC (Tabatabaei et al., 2014). On the other hand, some researchers have modified the GLADIT index also to enhance the framework to assess the coastal aquifer vulnerability. For example, Chachadi (2015) used an indicator-based GALDIT index to evaluate and quantify the vulnerability magnitude of the coastal aquifer to seawater intrusion in Goa, India. Gorgij and Moghaddam (2016) introduced the simplified GALDIT index ("L-Level of groundwater" being replaced by "P-pumping rate") to assess the vulnerability of Azarshahr Plain Aquifer, East Azerbaijan, Iran. Kazakis et al. (2018) applied a fuzzy approach to modify the framework of GALDIT to evaluate the vulnerability of coastal aquifer in the north of Greece. Bordbar et al. (2019)

used statistical and entropy models to modify the GALDIT framework to improve the evaluation index to assess the vulnerability of coastal aquifer to seawater intrusion in the province of Golestan, Iran. Kazakis et al. (2019) expanded the GALDIT index by adding the potential SUSI (SUperficial Seawater Intrusion) to assess groundwater salinization in the region of Italy and Greece.

Literature review shows that assessing coastal aquifer vulnerability is essential for coastal groundwater resources management. Since it is challenging to determine the threat of seawater intrusion and other factors at the local and regional levels, improved indices can be used to deal with different natural or anthropogenic mechanisms of coastal aquifer salinization at the specific area of interest (Kazakis et al., 2019). Thus, this study aims to expand the GALDIT index in a geographic information system (GIS) environment by using three significant parameters of the DRASTIC index and adding landuse of the study area to determine the influence of natural or human activities on the island aquifer vulnerability. The hierarchical analytical process (AHP) is used to build the GALDIT-NUTS index, while the electrical conductivity (EC) value is used to validate the index. The modified index can effectively identify the highly vulnerable aquifer zones and classify the factors responsible for aquifer vulnerability on an island. Besides, the targeted outcome of the present study is the generation of baseline information on the vulnerability of the coastal aquifer of the island of Favignana that would help the coastal planners for aquifer management.

2. Study Area

The Island of Favignana is located about 5 km from the north-west coast of Sicily in Italy, covering around 20 km^2 of geographical area (Fig. 1). It is the largest island of the Egadi archipelago along with the Marettimo and Levanzo islands in Italy (Colonese et al., 2011). The island is divided into two plain lands (eastern and western) by the Monte Santa Caterina hill with an elevation of 320 ma.s.l. (meters above sea level). Favignana island is a place of historical and environmental importance and an attractive place for tourism during the summer period in southern Italy (Falconi et al., 2015). It has a typically South Mediterranean climate, categorized by hot and dry summer and wet winter. The island has a slight fluctuation in temperature with an average value of around 27°C in summer and about 10°C in winter (Colonese et al., 2011). The island's economy is mainly based on tourism with limited input from agriculture and pastoralism. However, fishing (especially red tuna) and the mining of calcarenite rock were primary economic sectors in the past on the island (Groppi et al., 2018).

The Egadi Archipelago illustrates the outcrop of the submarine mountain chain linking the Maghrebid-Sicilian chain with the Tunisian one. Accordingly, the Favignana island represents an orogenic prism made up of several tectonic corps (Abate et al., 1997). These tectonic phases produced two main tectonic units, i.e., the Monte Santa Caterina Unit (upper one) and the Punta Faraglione Unit (lower one), and the island geological setting has the superposition of these two principal tectonic unites (Incandela, 1995; Abate et al., 1997). The geology of Favignana contains calcareous-dolomitic rocks dating from the Triassic to the Miocene, which form the chief relief in the centre of the Favignana island (Monte Santa Caterina, 320 m a.s.l.). Pleistocene calcareous and arenaceous marine sediments were successively deposited on the western and eastern plains of the island, respectively (Agnesi et al., 1993).

2.1. Hydrogeological setting

The hydrogeological map and cross-section of the study area (Fig. 1) provide information on the lithological composition, rock permeability, groundwater flow directions, groundwater availability, aquifer productivity and well distributions. The island has two plains (east and west) and the central ridge (Fig. 1). The island has three significant hydrogeological complexes (i.e., calcarenites, carbonate, and conglomerates and sand) and is hydraulically connected to each other (Tavarnelli et al. 2003). Moreover, the north-western plain of the island (Punta Sottile) is displaced by strike-slip and normal faults oriented from NW-SE to W-E. The groundwater level of the island was recorded maximum of 5 m. b.g.l. (meters below ground level) in the eastern plain (Tiwai et al., 2019). The morphology of the groundwater level depends on several local factors, such as the geological settings, hydraulic properties, and anthropogenic activities (Tiwari et al., 2019). On the west of the island, the piezometric surface slopes southwest wards with a hydraulic gradient ranging from 0.25 to 0.05% (Fig. 1). The highest hydraulic gradients are observed in the northern part of the aquifer due to the lower permeability of the deposits. On the east of the island, the piezometric surface slopes with a hydraulic gradient very low about 0.05% towards the eastern part a piezometric dome with surface slopes southwest wards and a hydraulic gradient ranging from 0.3 to 0.1% can be found.

3. Methods

Aquifer vulnerability assessment is significant for identifying the maximum potential zone for aquifer contamination based on hydrogeochemical and anthropogenic factors (National Academy of Sciences, 1993). Therefore, a modified index has been developed to assess the Island aquifer vulnerability in the present study (Fig. 2). Groundwater chemistry data of the island of Favignana were taken from Tiwari et al. (2019). Details concerning the Favignana Island groundwater sampling and analysis, quality control and concentrations of elements are described elsewhere (Tiwari et al., 2019).

3.1. Galdit index description

The GALDIT index was developed by Chachadi and Lobo Ferreira (2001) to assess the seawater intrusion of the coastal aquifer in different hydrogeological settings. The GALDIT index considers six essential parameters; **G**roundwater occurrence (aquifer type; unconfined, confined and leaky confined), **A**quifer hydraulic conductivity, depth to groundwater **L**evel above the sea, **D**istance from the shore (distance inland perpendicular from the shoreline), **I**mpact of the existing status of seawater intrusion in the area and **T**hickness of the aquifer which is being mapped (Table 1).

From these, the GALDIT Index is calculated as:

$$GALDIT\ Index = (W_G x\ G) + (W_A x\ A) + (W_L x\ L) + (W_D x\ D) + (W_I x\ I) + (W_T x\ T) \quad (1)$$

Where, W_p are the relative weights defined for the six parameters.

3.2. Drastic index description

The Environmental Protection Agency of the USA developed the DRASTIC index in 1987 to assess the potential for groundwater contamination (Aller et al., 1987). The DRASTIC index is developed based on the hydrogeological parameters that influence groundwater occurrence and interactions in the aquifer system. This method is an extensively used method for calculating the intrinsic vulnerability of aquifer to contamination (Rupert, 1999). The DRASTIC index considers seven essential parameters: **D**epth to groundwater, **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone and Hydraulic **C**onductivity (Table 2).

From these, the simple DRASTIC Index is calculated as:

$$DRASTIC\ Index = (W_D x\ D) + (W_R x\ R) + (W_A x\ A) + (W_S x\ S) + (W_T x\ T) + (W_I x\ I) + (W_C x\ C) \quad \textbf{(2)}$$

where W_p are the relative weights defined for the seven parameters.

3.3. Galdit-NUTS index description

The present study aims to expand the GALDIT index by adding four new parameters. Three parameters (i.e., Net Recharge (N); Topography (T); Depth of Groundwater Surface (S)) were taken from the DRASTIC index, and fourth parameter (Land Use (U)) was derived from remote sensing data in GIS environment (Fig. 2). The GALDIT-NUTS index has been calculated as:

$$GALDIT - NUTS\ Index = (W_G x\ G) + (W_A x\ A) + (W_L x\ L) + (W_D x\ D) + (W_I x\ I) + (W_T x\ T) + (W_N x\ N) + (W_U x\ U) + (W_T x\ Topo) + (W_S x\ S) \quad \textbf{(3)}$$

where, W_p are the relative weights assigned to the ten parameters (Table 3).

The score assigned to each weight was validated using the AHP method. This approach has already been used to validate new methodologies or new scores assigned to established methods, such as DRASTIC or GALDIT, in areas where the full scale of parameters was not present (Nasri et al., 2021; Neshat et al., 2014b; Thirumalaivasan et al., 2003; You et al., 2011).

3.5. Analytical Hierarchical Process (AHP)

For the method development, several procedures were analyzed (Javadi et al., 2020; Boardbar et al., 2019) to determine the most relevant parameters the relative weights for each parameter. Among these methods, the AHP has been chosen for the study because of its easy applicability and reproducibility in similar cases (Nasri et al., 2021; Faal et al., 2021). The AHP is a decision-making method that involves establishing multiple-choice criteria into a hierarchy, estimating their relative value, comparing alternatives for each criterion, and deciding an overall ranking of the alternatives (Saaty, 1986; Zaree et al., 2019). It is based on consistent matrices' well-defined mathematical structure and the right eigenvector's ability to produce true or approximate weights (Merkin, 1979; Saaty, 1980; Saaty, 1994). The AHP technique compares criteria to new GALDIT-NUTS weights or alternatives to a criterion in a normal, pairwise mode. The AHP accomplishes this by using a fundamental scale of absolute numbers that has been proved in reality and tested by physical and decision-making dilemma experimentations. Individual preferences are transformed into ratio scale weights, which can then be combined into a linear additive weight w(n) for each of the n options. The resulting w(n) can be used to rate and evaluate the alternatives (You et al., 2011). The three basic steps are logical descriptors of spontaneously resolving a multi-criteria decision problem. Its validity is founded on the thousands of practical implementations in which the AHP findings were approved and used by cognizant decision-makers (DMs) (Saaty, 1994). The weight of the most significant factors is higher, and vice versa. This technique was used to determine the appropriateness of the weights chosen. The CR (consistency ratio) is a valuable tool for determining the accurateness of the weights.

3.6. Validation of results using electrical conductivity

Electrical conductivity (EC) and total dissolved solids (TDS) are water quality parameters used to describe salinity levels. These two parameters are significantly correlated, and a simple equation usually expresses TDS: TDS = k EC (at 25^0C). An average k value of 0.63 is appropriate for brackish water with an EC range of 2000 to 20,000 μs/cm (Walton 1989). Some researchers have used TDS concentration to validate the aquifer vulnerability, including coastal aquifer (Khan et al., 2010; Bordbar et al., 2019; Bordbar et al., 2020; Javadi et al., 2020). However, in the present study, EC values were used to validate the results of all three methods since it is an excellent indicator of chloride content and salinity *(more details in sections 4.1.5 and 4.3.4.)*. Moreover, electrical conductivity is an ideal indicator parameter to monitor the changes in water chemistry that might arise at locations that are at risk from seawater intrusion.

4. Result and Discussion

The two most popular indices, GALDIT and DRASTIC, have been used in the present study, and these indices eventually depict their non-correlation with the control parameters. Analyzing the actual situation and the availability of reliable data concerning the geological, hydrological, geomorphologic, climatic characteristics; an alternate index GALDIT- NUTS has been developed. The AHP has been used to develop the index model (Kazakis et al., 2015) and determine each parameter's adequate and coherent weights.

Furthermore, the modified index was validated using the study area's groundwater electrical conductivity (EC) values. The selected approach suggests the robustness and representatives of the GALDIT-NUTS index where seawater intrusion and human factors play a crucial role in groundwater vulnerability. A comprehensive investigation of the method is discussed below:

4.1. Mapping of GALDIT Index

The first application of this method gave good value to the island because a large part of the island fell in high and medium vulnerability zones, and only a small part in the north has a low vulnerability (Fig. 3). Consequently, it has been opted by many other authors (Allouche et al., 2017; Kazakis et al., 2019; Parizi et al., 2019; Nasri et al., 2021) to increase the 4 standard rating steps of subdivision of the GALDIT into 10 steps to uniform it with the DRASTIC index.

To speed up the application of the method, the 10 classes derived from different applications have been used to create 4 polynomial curves (Supplementary Table 1).

Using the model builder, an ESRI ArcGIS tool to create flow processes and these curves in a GIS environment, the original maps derived from samplings on the island has been converted into parametric maps. It was necessary to add two process blocks to filter out values above or below a certain threshold. These values were returned to the maximum (10) or minimum (0) value.

4.1.1. Groundwater Occurrence, G

The progression of the sea intrusion into the groundwater depends on the parameter G (aquifer type). From the electrical conductivity (EC) values of the different wells, it is depicted that the aquifer is leaky and unconfined. The relative value of this type of Groundwater Occurrence assigned moves from 7.5 to 7 because in this study, to compare GALDIT and DRASTIC, it is preferred to use a 10-scale instead of a 4-scale (Fig. 4).

4.1.2. Aquifer Hydraulic Conductivity, a

Hydrogeological complexes in the present study area show values of hydraulic conductivity from 10^{-5} and 10^{-3} m/s. The maximum value was observed in the massif, where the carbonate complex is characterized by calcareous and dolomites. The eastern calcarenite outcrops are not uniform, with little lenses not in continuity with each other, reflecting local variations of permeability of about 10^{-4}. In the western sector, outcrops of carbonate rocks are more abundant, and conglomerate, sands and clay banks are relatively scattered, showing medium-low conductivity values (Tondi et al., 2016). In Table 4 indicates the values and rating of each parameter.

Here, it is divided into 10 classes (Fig. 4), and to evaluate the rating of Aquifer Conductivity (A) from the DRASTIC and SINTACS tables (Civita and De Maio 1997). The same ratings are used in the DRASTIC Aquifer Conductivity (C) to uniform the two methods.

4.1.3. Groundwater Level, L

Groundwater level related to the mean height of the sea is a highly important factor in assessing the seawater intrusion of any coastal region. A piezometric level measurement campaign was conducted in a dry and wet period, and the dry values were chosen for this work. The dry period is characterized by higher temperatures, low rainfall, and major exploitation of the aquifer. This map (Fig. 4) is derived by using software to interpolate using simple kriging. In particular, the minimal values of groundwater level below the sea level or the values < 1 m a.s.l. are most significant because the water intrusion in these circumstances is most likely. Favignana island shows values of height of water table between 0 to 3 m a.s.l.

4.1.4. Distance from the Shore, D

In many cases, the influence of seawater intrusion, moving perpendicularly to the shore towards the interior, generally decreases. Starting from the elevation of different points that form the digital elevation model (DEM) and using the polynomial curve, it was possible to estimate all 10 ranges. The values of D start from the value 10 near the shore and reach a minimum value of 1 in the east side of the area. The minimum value is also depicted in the proximity of the conglomerates plain (Fig. 4).

4.1.5. Impact of Existing Status of Saltwater Intrusion, I

The water table is few tens of centimeters above sea level in the western and eastern sectors, highlighting the poor groundwater resource all over the island (Fig 4). Moreover, the water table shows no significant differences between the wet and dry seasons, limiting to a few centimetres. According to the correlation between electrical conductivity values and chloride concentration (EC vs Cl = R^2 0.83) all over the island, three mean seawater intrusion flow directions are distinguishable along the coastal margin (Fig. 5). In 2009 the measured electrical conductivity in the wells of the western region varied from 2200 to 8500 µS/cm, with a maximum of 8500 µS/cm in the well no.1. However, concentrations of EC ranged from 850 µS/cm to 4720 µS/cm in the wells of the eastern part of the study area.

The chloride contour map (Fig. 5) facilitates identifying the seawater intrusion's main directions along the coastline. To understand the geochemical trends in the study area, groundwater sites were divided into groups 1 with 17 wells and 2 with 8 wells (Fig. 5). It is observed that the sample sites close to the carbonatic relief have similar geochemical trends constituting a little far group of sites in the easternmost sector attributed to their geo-environmental isolation.

4.1.6. Thickness of the Aquifer, Z

Hydrogeological or geological maps were used to determine the aquifer thickness for all sections. However, identifying the aquifer's thickness using the maps does not have good precision, which can otherwise be obtained from a geophysical campaign survey or using the wells drilling report. Nevertheless, considering that geological sections the complexes reach a depth of more than 20 m in respect of the water table, a value of 10 for this parameter finely describes the whole island's real situation (Fig. 4).

4.1.7. Galdit map description

Few parameters strongly influence the GALDIT index, particularly the distance from the shore (D). In fact, in a small island like Favignana, factor D deeply controls the analytical process, producing a final vulnerability map (Fig. 6) far from real seawater intrusion trends. Furthermore, the final GALDIT vulnerability map shows a low correlation with the electrical conductivity distribution (Fig. 7), since the GALDIT approach does not consider the factors of the groundwater recharge and its infiltration process. Under natural conditions, aquifer settings and recharge processes influence the groundwater flow, particularly the freshwater seaward movement that prevents seawater from encroaching on coastal aquifer. Table 5 shows the different percentages of territory divided by vulnerability.

4.2. Mapping of DRASTIC Index

The DRASTIC map of the study area was implemented based on the field trips of 2009 and 2010, using the available literature about geology and hydrogeology of the island, Sicilian soil classification and use maps, and the meteorological data.

Starting from the original methodology of DRASTIC, the polynomial curves have been defined that, subsequently, have been used in a GIS environment to create the raster maps for each parameter (Supplementary Table 2).

4.2.1. Depth to water table (D)

In 2009 and 2010, different wells were sampled, not necessarily the same in the two different campaigns, however, the groundwater depth values in the unconfined shallow Favignana aquifer depicted a range from 0 to 5 m in the areas near the north-west cape and in the territory where the island is narrow (Violet color in the D map). A depth of> 30 m was found near the left side of Santa Caterina mountain (brown color). These groundwater levels were organized into 10 classes (Fig. 8). However, a low water depth represents high vulnerability zones (violet color).

4.2.2. Net recharge (R)

The annual meteorological data obtained from the SIAS (Servizio Informativo Agrometeorologico Siciliano) depicted the mean total annual rainfall to be 450 mm for the study area, while the mean temperature in summer is 26°C and while during winter it is 12°C (Pappalardo et al., 2021). These values were derived from the analysis of the closest meteorological station that is on the mainland near the city of Trapani. No model was used to estimate the net recharge because all rainfall water on the island feeds the underlying aquifer or is collected for irrigation purposes. Thus, the arbitrary value of 450 mm per year was used to determine the R parameter (Fig. 8).

4.2.3. Aquifer media (A) and Impact of vadose zone (I)

The structure of the Favignana aquifer consists of three geological formations. Near the Santa Caterina mountain, different fault families have been found that modified the structure, but there is no evidence of complex vertical stratification. Therefore, the rating of aquifer media and the impact of the vadose zone was estimated according to the hydrogeological maps and different works on the study area that illustrated the porosity of different lithologies. The island is thus divided into three complexes depending on different hydrogeological characteristics, and for these intervals, a rating from 6 to 9 was assigned (Table 4). There is no evidence of vertical stratification of the different geological layers before reaching the water table, so the same rating was assigned to the two parameters (Fig. 8).

4.2.4. Soil media (S)

The soil is absent or thin on the island, and there is limited pedological information to calculate soil (S) of the study area. Therefore, a rating of 10 was used for soil (Fig. 8).

4.2.5. Topography (T)

The terrain model is based on the DEM (digital elevation model) from the INGV (Istituto Nazionale di Geofisica e Vulcanologia). The DEM of the Favignana Island shows a cell dimension of 2×2 m, and it was realized by a lidar fly in 2008. The DEM was geo-coded in WGS-84 lat long, with horizontal and vertical accuracies of ±15 cm and ±30 cm, respectively (Pappalardo et al., 2021). The higher elevated slopes are present in the centre of the island where S. Caterina Mountain divides the territory in two-part and near the south-west and east coast where the cliffs are sheer above the sea. Except for the central part of the island, which is characterized by the carbonate massif, the rest of the island is flat and consequently has a high rating (Fig. 8).

4.2.6. Hydraulic conductivity (C)

For a uniform computation, the hydraulic conductivity rating (Fig. 8) used is the same as the GALDIT index, and it was assigned using the DRASTIC and SINTACS tables.

4.2.7. Drastic Vulnerability index

The DRASTIC vulnerability map (Fig. 9) shows that the island of Favignana has five types of vulnerability as per modified DRASTIC classification (Musálem et al., 2015). The island has medium-low (< 140) in the small part in the south of the Santa Caterina Mountain while medium-high (141–160) in the western part. Values of 160-179 are illustrated on the left side of the central massif. Then a rapid succession is registered on the left side from medium-low to maximum in the SE-NW direction, owing to the groundwater depth. Also, the maximum value coincides with the zones of high permeability and conductivity (carbonates, conglomerates) and low water depth (0-5 m). On the other hand, the right side of the Santa Caterina Mountain has values from 180 to 200 in most of the territory of the eastern plain. Values of extreme vulnerability were recorded where the island is narrower and near the town of Favignana (Fig. 9). Besides, the low slope areas, varying from 0 to 3%, represent a favourable condition for the infiltration of contaminants from the surface. However, the DRASTIC vulnerability map shows a low correlation with the electrical conductivity distribution (Fig. 10), which may be attributed to the fact that the approach does not take into consideration the factors of the groundwater recharge and its infiltration process. Table 6 shows the different percentages of territory divided by vulnerability.

4.3. Validation of GALDIT-NUTS index

4.3.1. The proposed GALDIT-NUTS index for island vulnerability

The most important and easy-to-find parameters for territories with such characteristics have been included as parameters for this modified methodology. The GALDIT parameters were retained, and the following parameters were added from DRASTIC:

- Net Recharge (N)
- Topography (T)
- Depth of Groundwater Surface (S)

Also, another parameter was added that is derived from remote sensing and is always up-to-date, which is landUse (U).

4.3.2. Landuse

On the many small islands in the Mediterranean Sea, the soil is absent or thin, and the pedological information is either scarce or does not provide a distinct characterization of the territory.

Human impact on natural processes can be identified from landuse. The parameter “landuse” has an important bearing on aquifer vulnerability assessment. Therefore, it is necessary to merge the pedological informations with land use to create a better vulnerability map. So in this study, the standard soil map used in the DRASTIC index was modified to have a better subdivision of the territory and the rating change from a unique 10 value into six intervals (Table 7). The rating presented in Table 7 has been assigned using the step-wise weight assessment ratio analysis (SWARA) (Keršuliene et al., 2010; Hashemkhani Zolfani and Bahrami, 2014).

4.3.3. Application of AHP method to validate chosen weights

The relative weights to the different factors that make up the GALDIT-NUTS method were determined to be representative of an area, such as an island, and after being assigned, a hierarchy analysis was applied through the application of the AHP approach that gave excellent results in other applications (Neshat et al., 2014b; Thirumalaivasan et al., 2003; You et al., 2011).

The AHP is a method based upon the construction of a series of Pair-Wise Comparison Matrices (PCMs). Using this type of comparison, all the criteria have been correlated to one another. Each a_{ij} entry in matrix GALDIT-NUTS represents the relative importance of the i_{th} criterion with respect to the j_{th} criterion.

$$GALDIT-NUTS_{Matrix} = \left[\begin{array}{ccccccccccc} & G & T & I & Topo\ (T) & L & D & N & U & A & S \\ G & 1 & 1 & 0.50 & 0.33 & 0.33 & 0.25 & 0.25 & 0.25 & 0.20 & 0.20 \\ T & 1 & 1 & 2.00 & 3.00 & 3.00 & 4.00 & 4.00 & 4.00 & 5.00 & 5.00 \\ I & 2.00 & 0.50 & 1 & 1.50 & 1.50 & 2.00 & 2.00 & 2.00 & 2.50 & 2.50 \\ Topo\ (T) & 3.00 & 0.33 & 0.67 & 1 & 1 & 1.33 & 1.33 & 1.33 & 1.67 & 1.67 \\ L & 3.00 & 0.33 & 0.67 & 1 & 1 & 1.33 & 1.33 & 1.33 & 1.67 & 1.67 \\ D & 4.00 & 0.25 & 0.50 & 0.75 & 0.75 & 1 & 1 & 1 & 1.25 & 1.25 \\ N & 4.00 & 0.25 & 0.50 & 0.75 & 0.75 & 1 & 1 & 1 & 1.25 & 1.25 \\ U & 4.00 & 0.25 & 0.50 & 0.75 & 0.75 & 1 & 1 & 1 & 1.25 & 1.25 \\ A & 5.00 & 0.20 & 0.40 & 0.60 & 0.60 & 0.80 & 0.80 & 0.80 & 1 & 1 \\ S & 5.00 & 0.20 & 0.40 & 0.60 & 0.60 & 0.80 & 0.80 & 0.82 & 1 & 1 \end{array}\right]$$

Then, a calculation was performed to find the maximum eigenvalue λ_{max} of matrix GALDIT-NUTS:

$$\mathrm{GALDIT-NUTS}\omega = \lambda_{max}\omega, \omega = (\omega_1, \omega_2, \dots, \omega_n)^T \qquad \textbf{(4)}$$

where ω_n represents the priority weight of the n_{th} criterion.

Moreover, using λ_{max}, it is possible to calculate the consistency index (CI) and the consistency ratio (CR) to verify the effectiveness of the comparison matrix GALDIT-NUTS.

$$CI = \frac{\lambda_{max} - n}{n-1} = 0.117 \qquad \textbf{(5)}$$

$$CR = \frac{CI}{RI} = \frac{0.142}{1.45} = 0.077 \qquad \textbf{(6)}$$

where, *n* is the order of matrix GALDIT-NUTS, *RI* is the mean random consistency index and can be determined by Table 8. If CR < 0.1, the comparison matrix conforms to the consistency standard (Lin and Yang, 1996). Distribution of consistency weight allowed creating a GALDIT-NUTS map to compare values from different control wells to the measured electrical conductivity values during two campaigns.

4.3.4. Outcomes of GALDIT-NUTS

The standard GALDIT index showed poor discrimination of seawater intrusion into the selected area, with only the coastline being classified as vulnerable to salinization. In general, the evaluation and weighting system of the standard method is not directly applicable to different hydrogeological settings, and the method must be recalibrated each time for each region analyzed.

On the contrary, even if the GALDIT-NUTS map has similarities with the standard GALDIT vulnerability, it has a better distinction with respect to the standard GALDIT maps and highlights the zones where saline surface water bodies interact with the groundwater system.

Application of the GALDIT-NUTS to Favignana Island revealed a highly vulnerable zone along the northwestern coastline, with the high, very high, and maximum vulnerability zones covering approximately 66.4% of the study area (Fig. 11). Medium (low and High) vulnerability characterizes 32% of the territory (Table 9), mainly in the hilly part of the island and a small part of the territory in the south of the watershed, where the depth of groundwater is very deep (Fig. 11).

The presence of areas of high vulnerability on the coast is mainly caused by the flat topography and the presence of subsided areas. The abandoned placer mining quarries along the coastal areas are highly susceptible to seawater intrusion due to the lateral movement of seawater through sandy aquifers. Various parts of coastal plains near human settlements have been identified as vulnerable zones where sandy aquifer are affected due to seepage of saline water through the process of seepage movement.

The aquifer vulnerability index needs validation to reduce the subjectivity in selecting ratings and increasing the reliability. The AHP method made it possible to recalibrate the weights assigned to each parameter. Changing these indices significantly improved the correlation between electrical conductivity and chloride concentration data. In particular, only the importance of the topography changed from 1 to 3 compared to the original method. In addition, the new landuse parameter that replaces the soil parameter in the DRASTIC index has been assigned a score of 4 (previously soil in the DRASTIC index was assigned the score of 2). Besides, Pearson correlation was used to evaluate the relationship between the final rating of vulnerability derived by the GALDIT-NUTS index and the electrical conductivity values that were chosen as seawater intrusion indicators. Thus, the vulnerability index has been compared with groundwater electrical conductivity to identify the real risk of seawater intrusion.

The plots of electrical conductivity vs GALDIT-NUTS (Fig. 12) show the better and increasing correlation index of the two different groundwater surveys of the study area. In the correlation analysis of electrical conductivity with GALDIT and GALDIT-NUTS the R^2 increases from 0.3997 to 0.8503 for Group 1, while for group 2, the increase in R^2 was from 0.0209 to 0.8327 in the study area. Moreover, in a similar comparison between the correlation of EC with DRASTIC and GALDIT-NUTS also depicts an increase in R^2 from 0.4508 to 0.8503 and from 0.3114 to 0.8327 for groups 1 and 2, respectively. Using GALDIT-NUTS, high EC values correspond to the high index values. Therefore, it is confirmed that the modified GALDIT-NUTS is an improved index to assess the Island aquifer vulnerability.

In comparison, the present correlation results with aquifer vulnerability indices outcomes suggest that the GALDIT-NUTS index provided more accurate results than DRASTIC and GALDIT indices. A similar approach has been followed by Bordbar et al. (2019) to assess coastal aquifer vulnerability in the province of Golestan of Iran using GALDIT and the modified GALDIT index. A correlation technique was used to determine the correlation between the vulnerability indices and suggested that the modified GALDIT framework based on the Wilcoxon entropy is a better index for assessing the aquifer vulnerability of coastal areas. Also, Kardan Moghaddam et al. (2017) used a correlation approach to validate the coastal aquifer vulnerability results of the vulnerability indices. Based on correlation results, an index was suggested that provided more accurate results for vulnerability mapping. Furthermore, the APH technique used in the present study to establish relative weights for each parameter to improve the accuracy of vulnerability has been used by other researchers also in coastal aquifers to assign factor weights (Kazakis et al., 2019; Nasri et al., 2021; Khosravi et al., 2021). Hence, the present study results suggest that the GALDIT-NUTS index is effective with improved accuracy of the weight factors to assess the Island aquifer vulnerability for water resources management.

5. Conclusion

The proposed index (GALDIT-NUTS), using the two existing methodologies (GALDIT and DRASTIC) and added landuse, solved many problems associated with the retrieval of data to evaluate the seawater intrusion and anthropogenic impact on the aquifer of small islands. The proposed index does not require the soil type or aquifer thickness data, which are difficult to find or non-existent. On the contrary, the proposed index uses landuse data which is easier to assess or possibly obtained indirectly with remote sensing. Moreover, the AHP technique which has been used in the present study, also proved to be an excellent methodology for verifying the old weights of the two vulnerability calculation systems and determining the new weights. Besides, electrical conductivity of the groundwater has been used to validate the vulnerability results of the area. Finally, the modified method can be deterministic in evaluating the results on the aquifer vulnerability and integrating the information related to possible pollution from natural (i.e., salt intrusion) or anthropogenic activities.

The present research demonstrated that the developed modified GALDIT-NUTS is a better index for assessing the Favignana Island aquifer vulnerability. The validation of the three methods' outcomes suggested that the GALDIT-NUTS is an improved index over GALDIT and DRASTIC indices to assess the Island aquifers since the influence of natural and anthropogenic factors on Island aquifer can be determined. Thus, the modified method can be helpful for the coastal planners to create a plan for aquifer management of similar Islands elsewhere across the globe.

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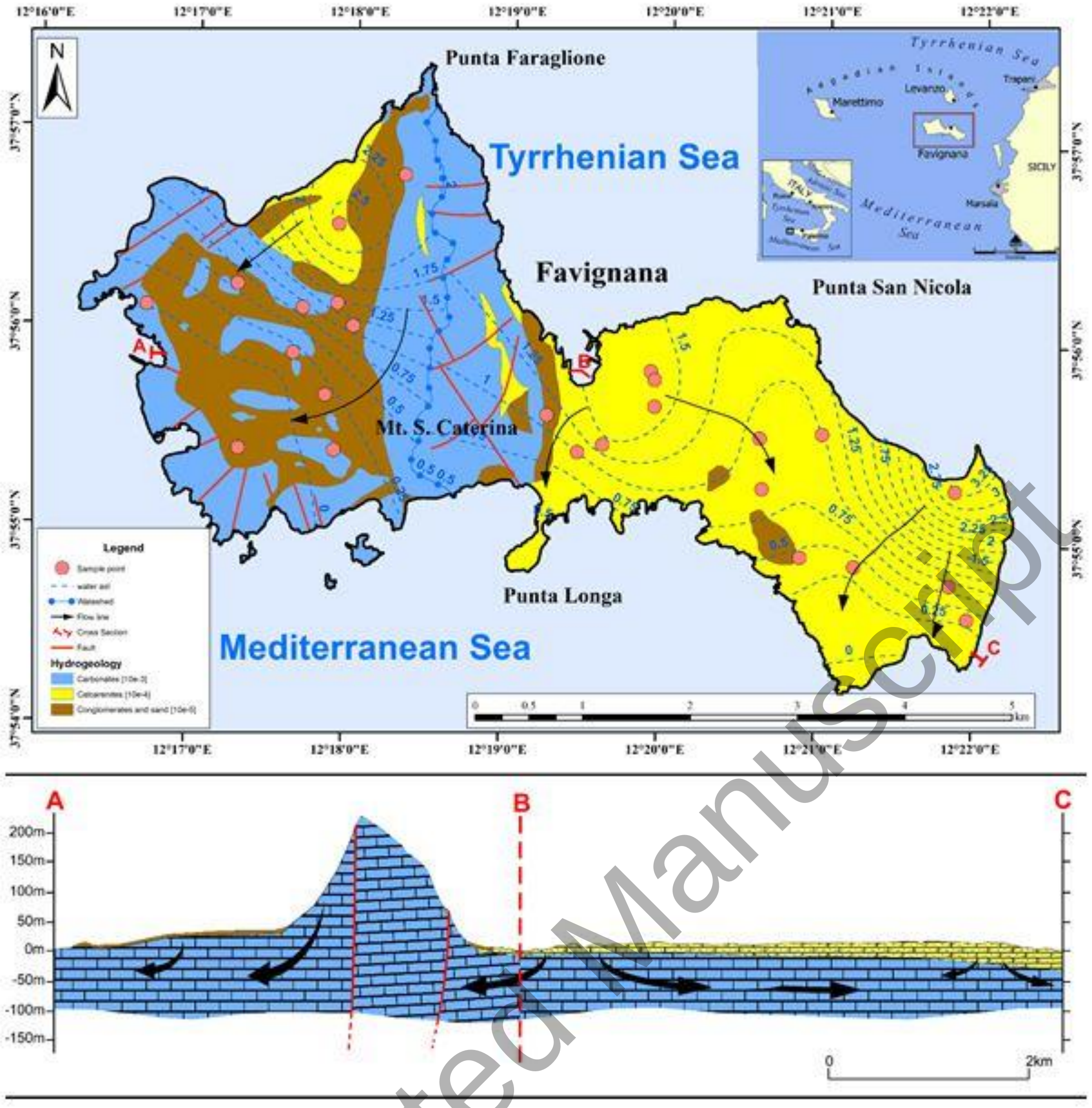

Figure 1. Location map of the study area with hydrogeological map and cross-section along line A-B-C.

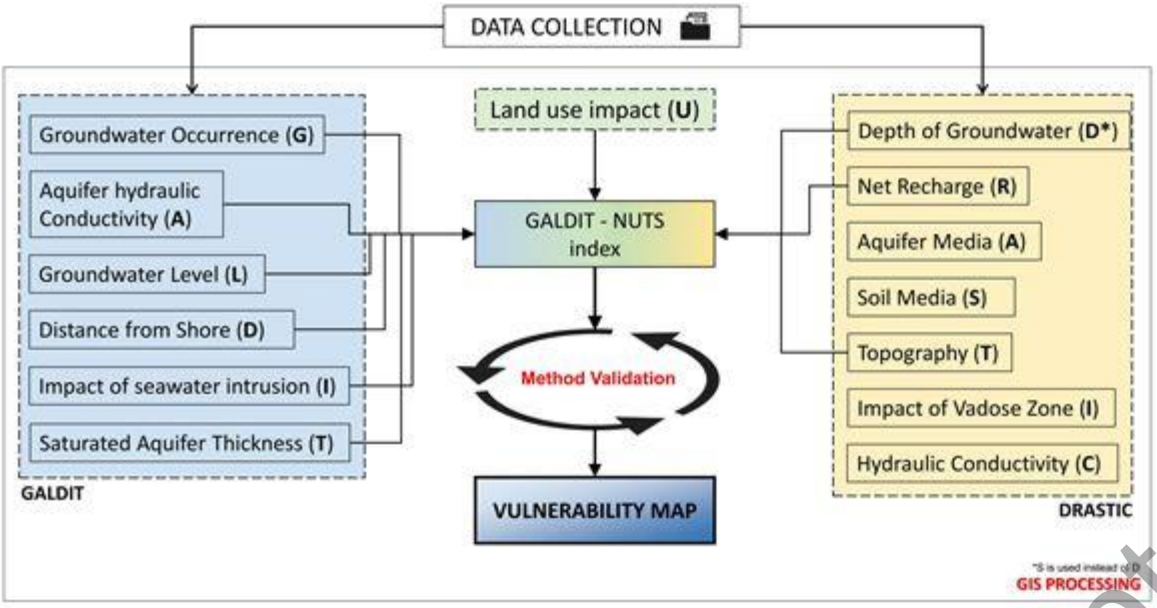

Figure 2. Methodology flow chart.

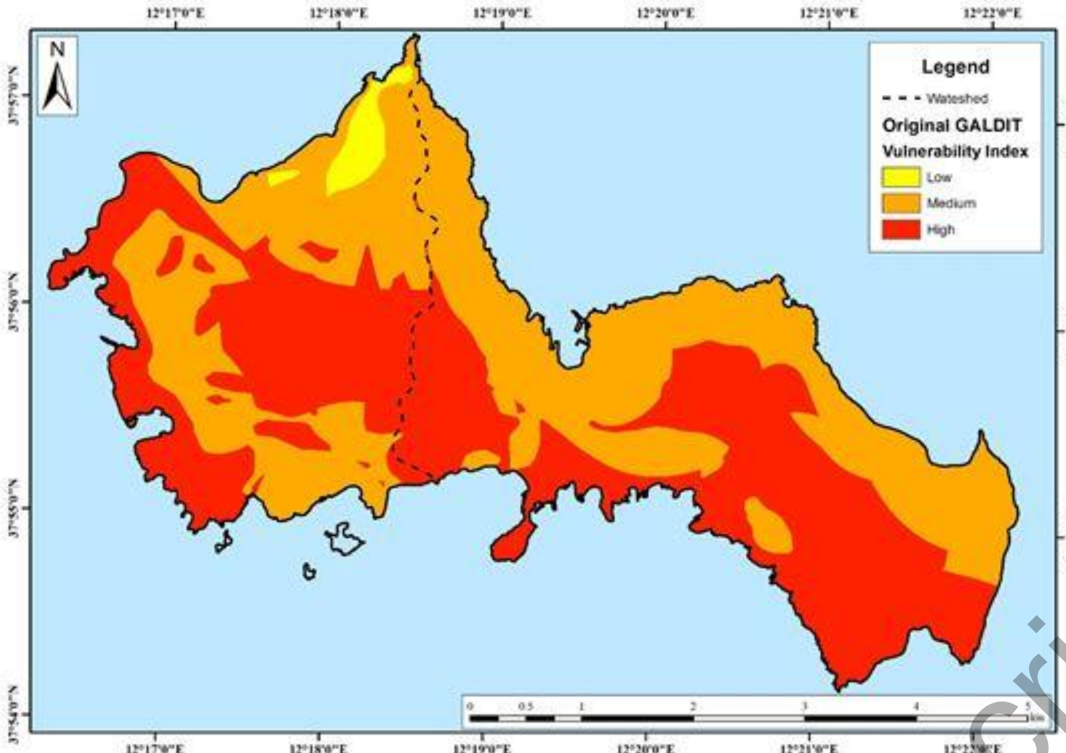

Figure 3. Aquifer vulnerability map of the study area using original GALDIT index.

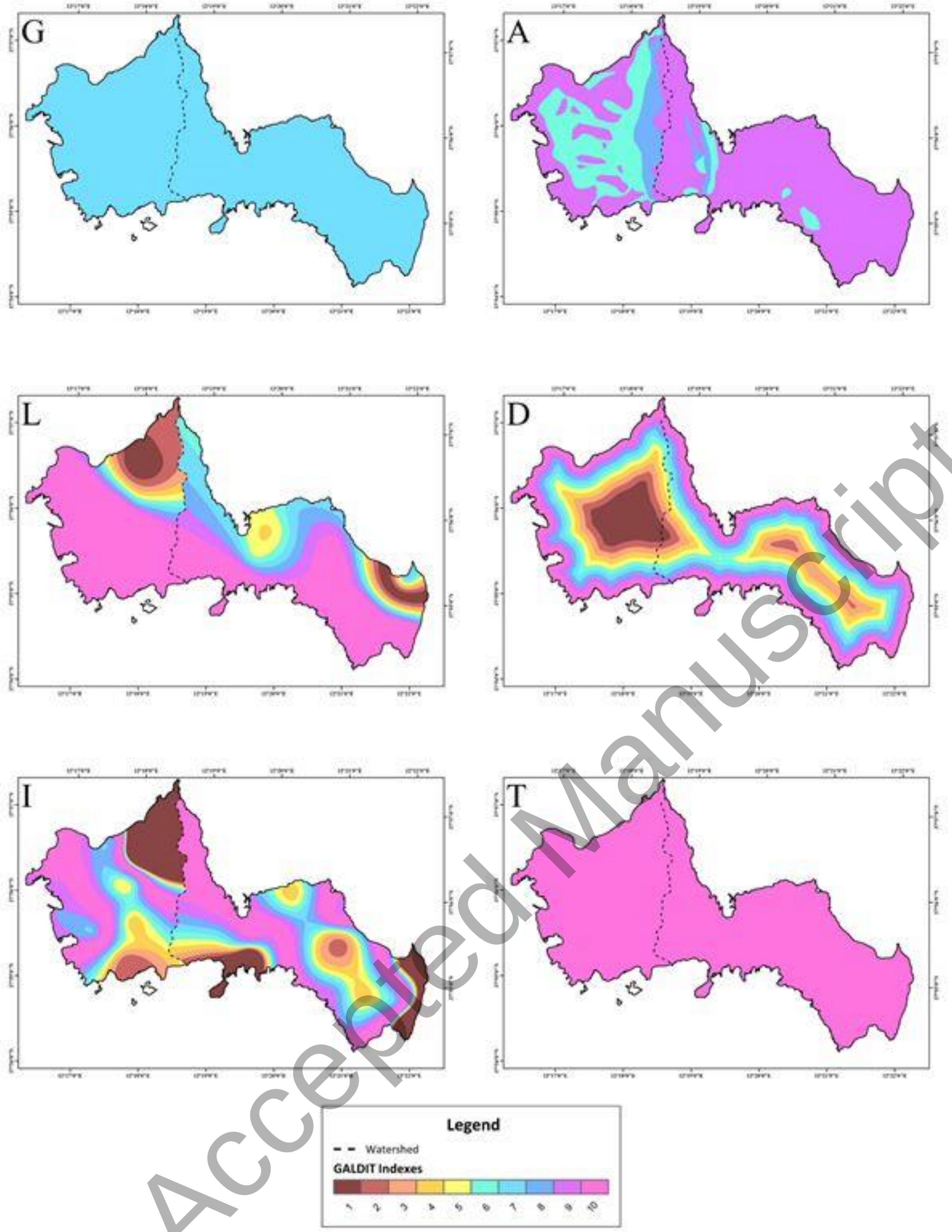

Figure 4. GALDIT parameters: G - Groundwater occurrence (aquifer type), A – Aquifer hydraulic conductivity, L – Height of Groundwater level above sea level, D – Distance from shore (m), I – Impact of existing status of seawater intrusion, T – Thickness of aquifer.

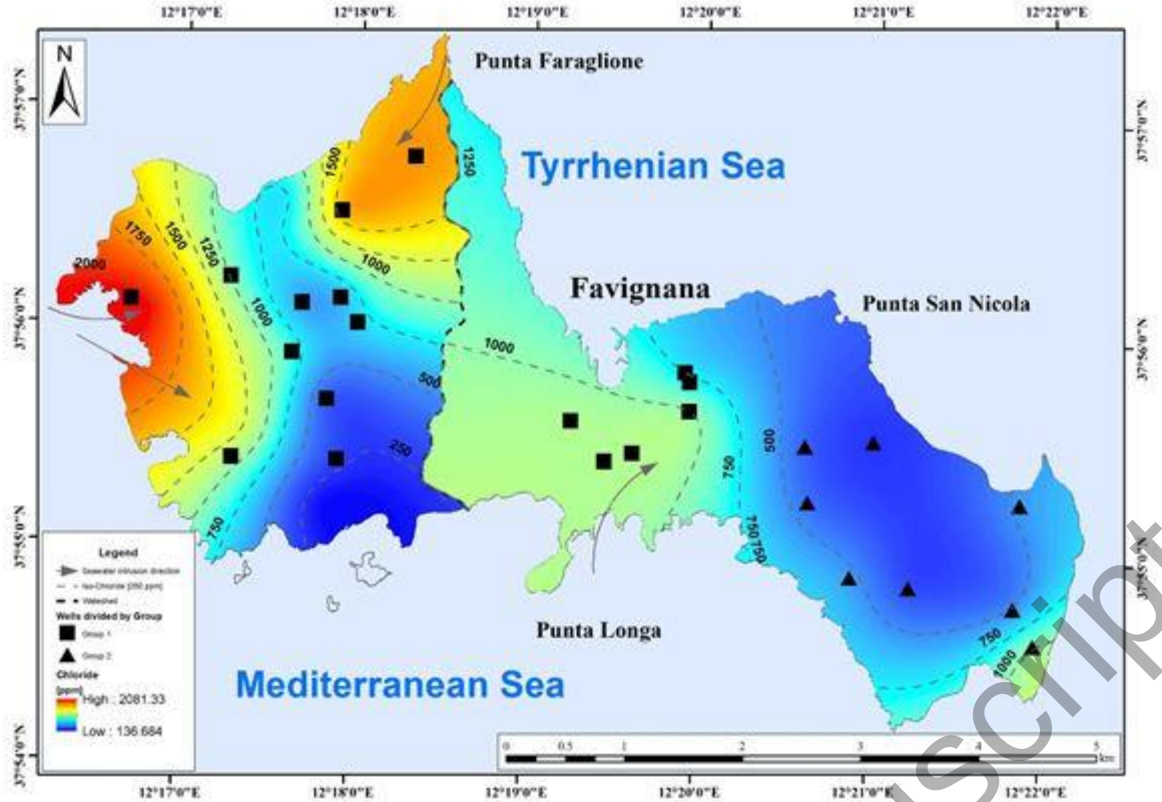

Figure 5. Chloride concentration of the Island.

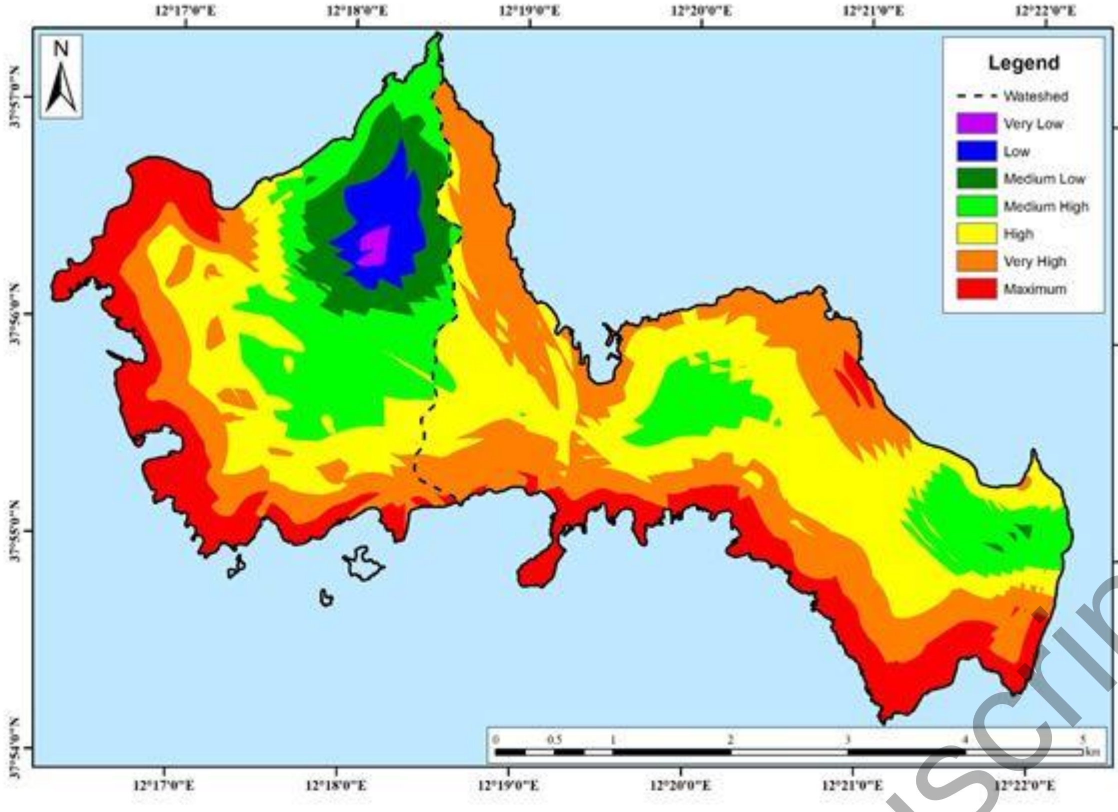

Figure 6. Aquifer vulnerability map of the study area using GALDIT index 10 classes.

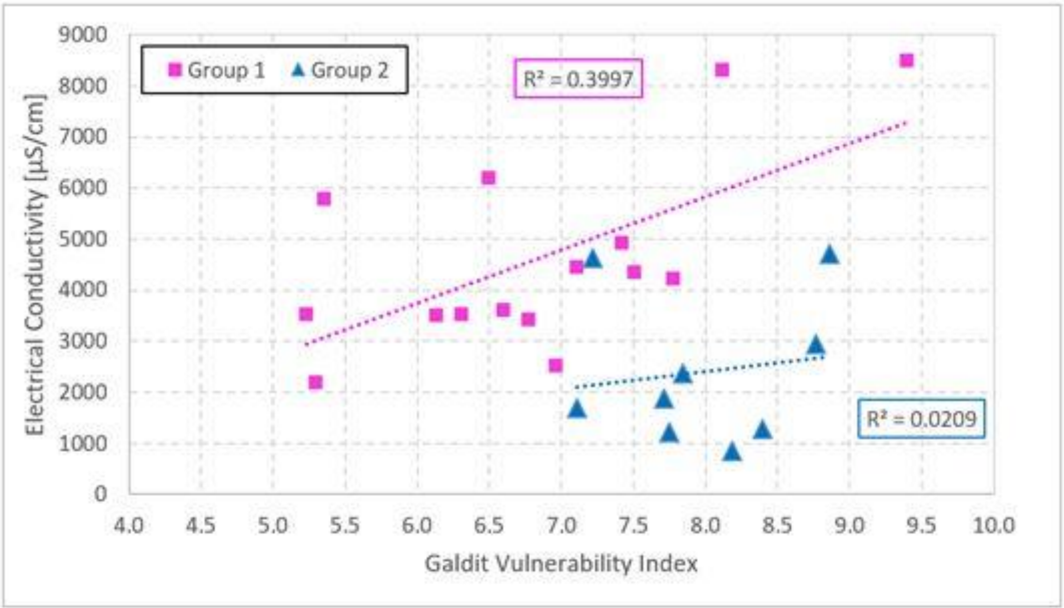

Figure 7. GALDIT Vulnerability Index Vs Electrical Conductivity.

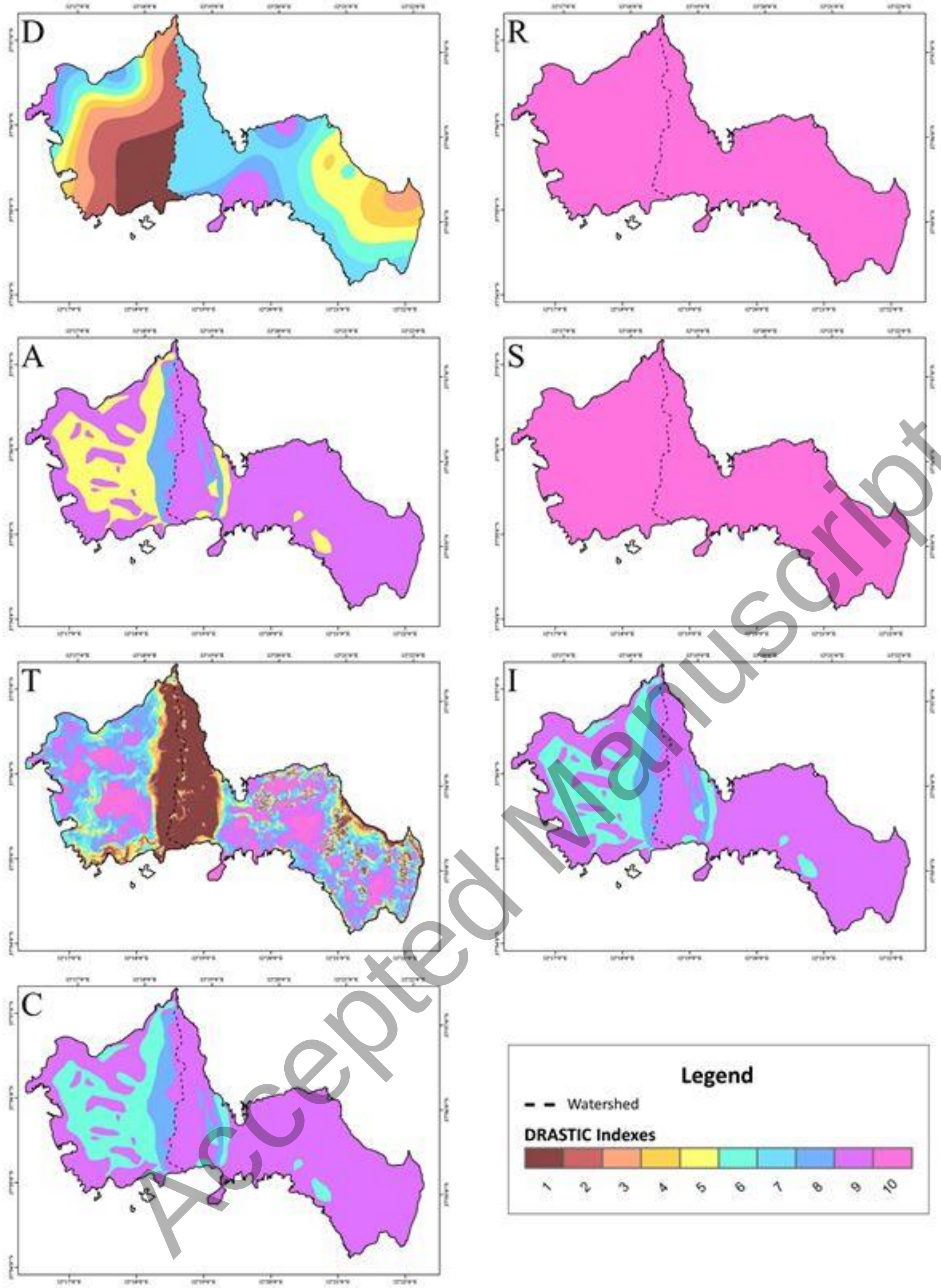

Figure 8. DRASTIC parameters: D – Depth of Groundwater, R – Net Recharge, A – Aquifer Media, S – Soil Media, T – Topography, I – Impact of Vadose Zone, C – Aquifer hydraulic conductivity.

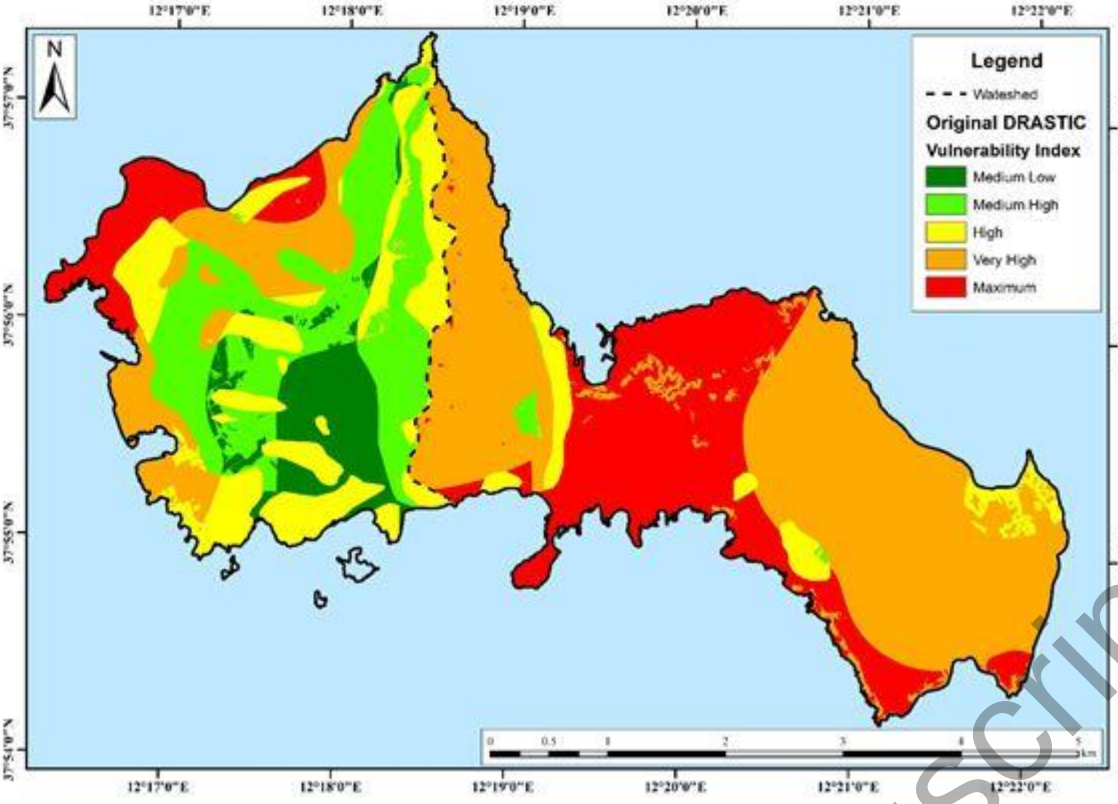

Figure 9. Aquifer vulnerability map of the study area using original DRASTIC index.

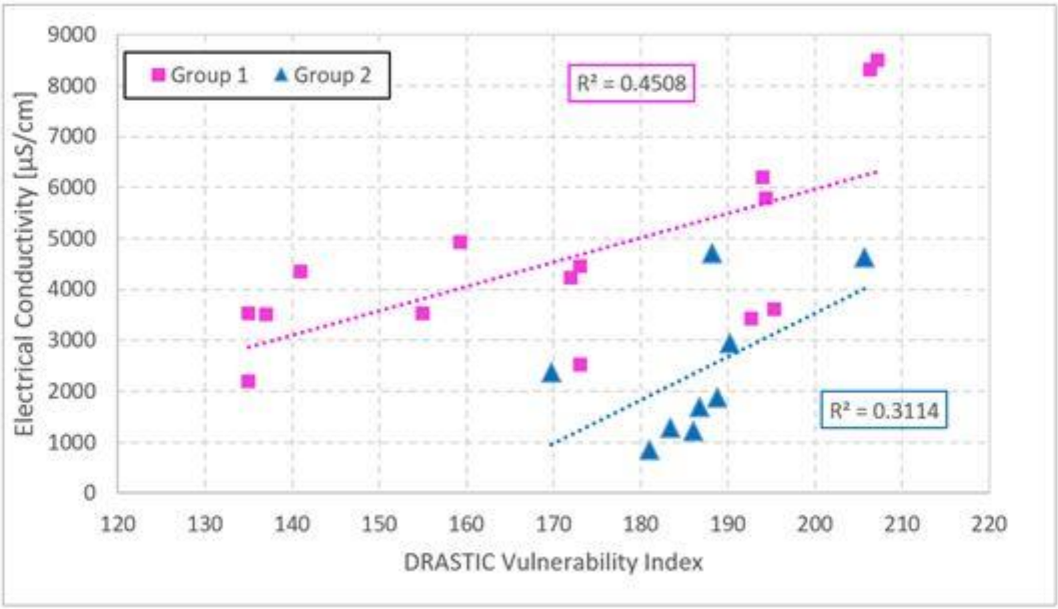

Figure 10. DRASTIC Vulnerability Index Vs Electrical Conductivity.

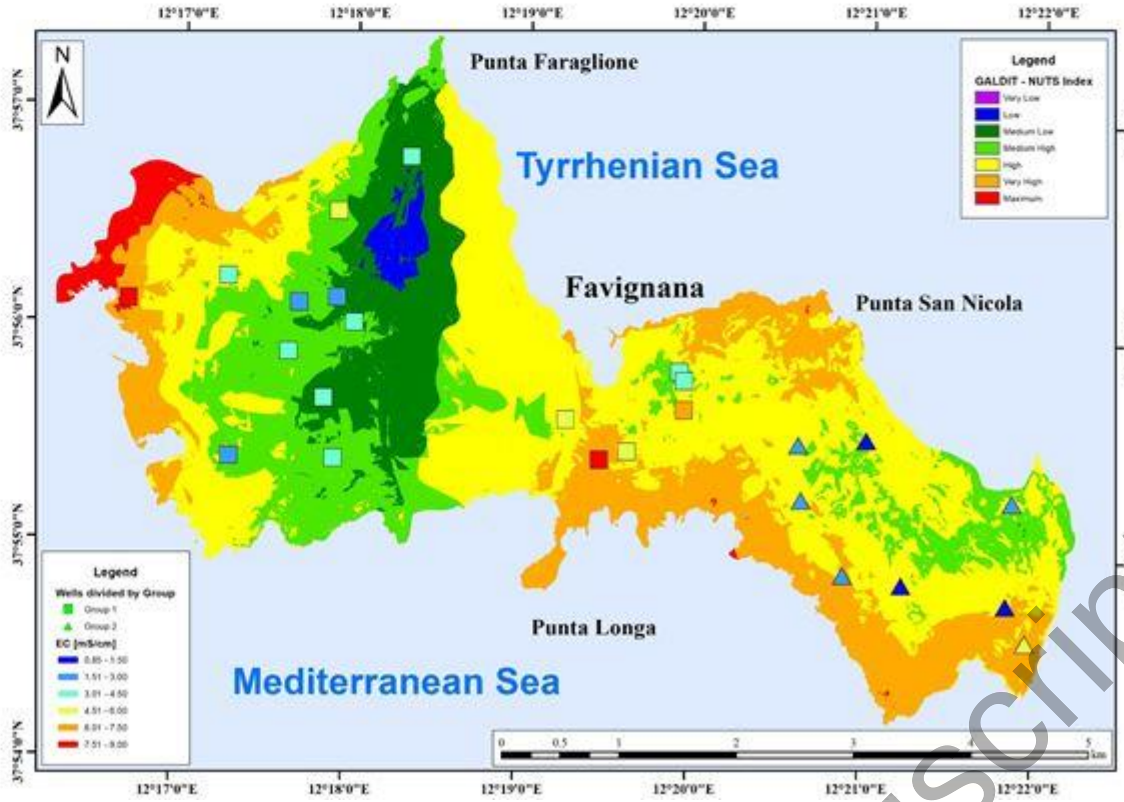

Figure 11. Aquifer vulnerability map of the study area using developed GALDIT-NUTS. Map with different wells divided by group; Square (group 1) and Triangle (group 2).

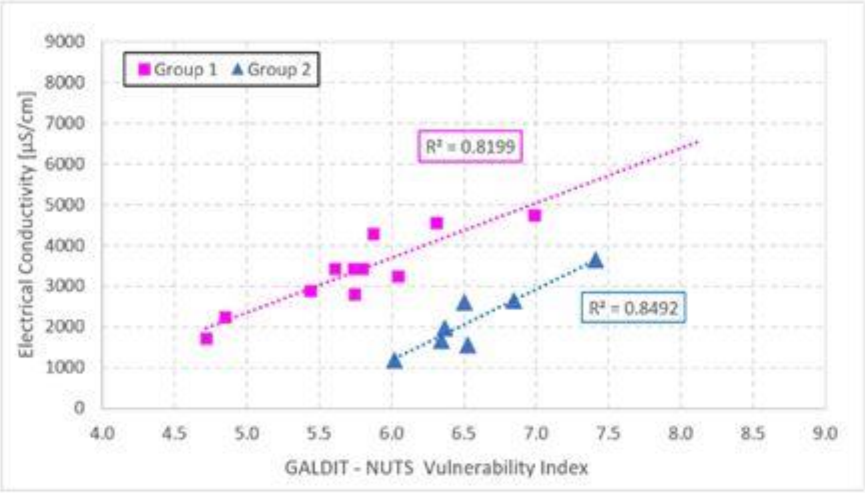

Figure 12. Correlation between different wells divided for the two groups (2009).

Table 1. Original GALDIT subdivision (Chachadi and Lobo Ferreira, 2001) of the study area.

Parameter	**Weight**	**Value**	**Original Value**
G - Groundwater occurence	1	Unconfined	7.5
A - Aquifer hydraulic conductivity	3	Conglomerates and sands Hydrogeological Complex	7.5
		Calcarenites Hydrogeological Complex	7.5
		Carbonates Hydrogeological Complex	10
L - Groundwater Level [m]	4	< 1	10
		1 < x < 1.5	7.5
		> 1.5	5
D - Distance from shore [m]	4	< 500	10
		500 < x < 700	7.5
		700 < x < 1000	5
		> 1000	2.5
I - Existing Impact [Cl^-/HCO_3^-]	3	< 1	2.5
		1.1 < x < 1.5	5
		1.6 < x < 2	7.5
		> 2	10
T - Groundwater Thickness [m]	2	0 − 3.77	10

Table 2 Original DRASTIC classes subdivision (Aller et al., 1987) of the study area.

Parameter	**Weight**	**Value**	**Original Value**
D - Depth of groundwater [m]	5	0 − 1.5	10
		1.5 − 4.5	9
		4.5 − 9	7
		9 − 15	5
		15 − 23	3
		23 − 30	2
		> 30	1
R - Net Recharge [mm]	4	450	10
A - Acquifer media	3	Conglomerates and sands Hydrogeological Complex	5
		Calcarenites Hydrogeological Complex	8
		Carbonates Hydrogeological Complex	9
S – Soil	2	No soil	10
T – Topography [%]	1	0-2	10
		2 < x < 6	9
		6 <x < 12	5
		12 < x < 18	3
		> 18	1
I - Impact of vadose zone	5	Conglomerates and sands Hydrogeological Complex	6
		Calcarenites Hydrogeological Complex	8
		Carbonates Hydrogeological Complex	9
C - Hydraulic Conductivity	3	Conglomerates and sands Hydrogeological Complex	6
		Calcarenites Hydrogeological Complex	8
		Carbonates Hydrogeological Complex	9

Table 3 GALDIT - NUTS Weights.

Parameter	G	A	L	D	I	T	N	U	T	S
Weight	1	5	3	4	2	1	3	4	3	5

Table 4 GALDIT Aquifer Hydraulic Conductivity (A).

C - Conductivity	**Value [m/s]**	**Rating**
Conglomerates and sands	1×10^{-5}	6
Calcarenites	1×10^{-4}	8
Carbonates	1×10^{-3}	9

Table 5 Original GALDIT index classes classification (Chachadi and Lobo Ferreira, 2001) and modified GALDIT index classes classification (Saidi et al., 2013) in the study area.

GALDIT				GALDIT 10 Classes			
Index Rate	Vulnerability classes	Area [m^2]	Percentage of coverage	Index Rate	Vulnerability classes	Area [m^2]	Percentage of coverage
< 5.0	Low	62504	0.3%	1 – 2	Minimum	-	-
				3 – 4	Very Low	62504	0.3%
5.0-7.5	Moderate	3030597	15.2%	5	Low	530856	2.6%
				6	Medium - Low	1029588	5.2%
				7	Medium - High	3515525	17.7%
> 7.5-10.0	High	16840346	84.5%	8	High	6043871	30.3%
				9	Very - High	5563528	28%
				10	Maximum	3161547	15.9%

Table 6 DRASTIC index classification from Aller et al. (1987) and interpretative values according to the index.

DRASTIC			
Index Rate	**Potential Vulnerability**	**Area [m^2]**	**Percentage of coverage**
< 120	Low	-	-
121-140	Medium - Low	1154262	5.8%
141-160	Medium - High	3003206	15.1%
161-180	High	2923015	14.6%
181-200	Very - High	8444611	42.4%
> 201	Maximum	4376275	22.1%

Table 7: LandUse (U) Classification.

Landuse	**Rating**	**Landuse**	**Rating**
City	0	Grass	7
Tree	8	Pasture (sheepcortile)	8
House without sewerage	8	House courtyard	7
Mines	10	absent	10
Little farming	5	Hotels and residences	8
Little farming (melons)	5	Olive grove	6
Little farming (prickly pears)	8	Vineyards	7

Table 8: Mean random consistency index RI.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Table 9 GALDIT - NUTS index classification from DRASTIC index Aller et al. (1987) and interpretative values according to the US national color code.

GALDIT – NUTS					
Index Rate	**Color**	**R, G, B**	**Potential Vulnerability**	**Area [m^2]**	**Percentage of coverage**
1-2	Violet	238, 130, 238	Minimum	-	-
3-4	Indigo	75, 0, 130	Very Low	-	-
5	Blue	0, 0, 25	Low	263677	1.4 %
6	Dark Green	0, 128, 0	Medium – Low	2265672	11.4 %
7	Light Green	0, 255, 0	Medium – High	4129215	20.8 %
8	Yellow	255, 255, 0	High	8682826	43.8 %
9	Orange	255, 127, 0	Very – High	4067354	20.5%
10	Red	255, 0, 0	Maximum	400485	2.1%