Limitations of GALDIT to map seawater intrusion vulnerability in a highly touristic coastal area

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Abstract. Coastal aquifers are susceptible to seawater intrusion, especially touristic areas where the overexploitation combined with the agricultural use of groundwater represent a severe issue for water management. GALDIT methodology was applied as a management tool to identify and prevent salinization of the aquifer. GALDIT methodology needs six input parameters: groundwater occurrence (G), aquifer hydraulic conductivity (A), groundwater head above sea level (L), distance from the shore (D), impact of the existing status of seawater intrusion (I), and thickness of the aquifer (T). Then a contour map is created using three degree of vulnerability: high, medium and low. The higher vulnerability zone ranges from 40 to 550 m towards the mainland with the rest of the aquifer characterized by medium vulnerability. The main problem affecting the selected field site is the large water requirement during the summer period due to the touristic activities, but the correct use of surplus water collected in the winter can overcome this problem. This study demonstrates that further investigation on groundwater hydrochemistry and on water demand trends from the different activities impacting the field site should be implemented, in order to guarantee environmental and touristic development sustainability.

1. Introduction
Coastal environments are under intense anthropogenic pressure due to urbanization, agriculture, tourism and industrial activities. Groundwater constitutes the main source for water supply in many coastal zones [1]. Tourism indeed represent an opportunity for economical grow for many countries, but it could generate also negative impacts. One of the most relevant is the impact on water resources, especially in coastal zones due to the overexploitation of the available water resources. Different study shows as, in many country, the summer touristic activities, could be responsible of negative effect on water resources in term of quality and availability, especially if no management plans are made [2,3]. Undeniably, the excessive dependence of coastal activities on groundwater triggers the research for alternative sources. Hence, the understanding of both quantitative and qualitative regimes of this invaluable natural resource constitutes the optimal solution to retain the costal environment sustainability. Seawater intrusion is one the major threats for coastal aquifer salinization. It is often
stimulated by overexploitation of groundwater causing negative piezometric heads and consequently reverse flow direction from the sea towards the mainland [4]. Although, also paleo-seawater intrusion can be detrimental in coastal areas [5,6]. There are several rating models, each one proposed for different areas, situation and dataset suitable for groundwater vulnerability assessment. GALDIT [7] is the one developed for coastal aquifer and with the analysis of just six parameters is the mostly used and modified [8,9] to assess actual seawater intrusion in littoral areas.

This article aims to illustrate the interconnection between touristic development and groundwater sustainability. Hence, the groundwater vulnerability map obtained applying the GALDIT method in a highly touristic coastal area of Greece has been used as a management tool to prevent salinization of the aquifer. However, questions arise regarding the completeness of this tool so as to provide a holistic appraisal for this persistent issue.

2. Field site
The Sarti basin is situated in northern part of Greece, within the Macedonia region in the Peninsula of Sithonia (figure 1).

Figure 1. Geological map with principal drainage network and roads of the coastal area of Sarti (modified from IGME map, Sheet: Peninsula of Sithonia [10]). A cross-section passing in the middle of the map is also provided in the lower right panel.
The study area extends for 18 km², has a shoreline of 1.8 km and a mean altitude of 220 m. The morphology is inconstant with an average slope of 32%; steep gradients are present in the hilly portion of the basin, while flat a topography is present near to the coastline. The study area has a Mediterranean climate, characterized by dry summers and wet winters with heavy rains.

The average yearly temperature and precipitation values are 15.9°C and 440 mm, respectively (Ormylia station). According to IGME (Institute of Geology and Mineral Exploitation) [11], the mean annual precipitation of the Sithonia Peninsula is 545 mm, 63.3% of which corresponds to evapotranspiration, 7.7% to infiltration and 29% to surface runoff. The majority of the study area is occupied by the Mesozoic granodiorite (Sithonia type) which is located mainly in the mountainous part of the basin. Holocene sedimentary formations dominate the lowlands and consist of alluvial deposits (gravel, sand and clay), coastal deposits (beach ridges, sand and dunes) and sediments of coastal lakes and lagoons (silt and clay with sand). Normal faults, with orientation WN–SE and E–W, have formed the actual structure of the basin.

In the basin, porous aquifers and fractured rock aquifers co-occur. Fractured rock aquifers are placed in the granodiorite and their yield can reach up to 15 m³/h. The porous aquifers are positioned in the Holocene formations and occur in confined and/or unconfined form, covering an area of 2 km². The aquifer hydraulic conductivity (K) values range from 1 to 41 m/day; the highest values are placed in the margin between the granodiorite and the alluvial deposits where gravels dominate. The aquifer width ranges between 20 to 50 m. The piezometric head ranges between 18 to -1 m above sea level (a.s.l.). The water request for drinking purposes and agricultural activities are mainly covered by the utilization of the porous aquifer. Additionally, seasonal springs and a small number of boreholes hosted in the granodiorite formation, contribute to the water supply of the region.

The Hellenic Statistical Authority census data (2011) states that the inhabitants are about 1,200. Touristic activities are constantly growing in Sarti, principally in summer and the population can reach up to 40,000 individuals. Indisputably, during summer the abstracted quantity of groundwater cannot be replenished and negative piezometric heads occur in the porous aquifer. Thus, the salinization of the coastal aquifer due to actual seawater intrusion will affect touristic development in the area, unless the local authorities will adopt a prevention policy to defend the coastal aquifer.

3. Methodology
The GALDIT methodology is constructed on six hydrogeological, hydrological and geomorphological factors [7,12,13]: groundwater presence (G), aquifer hydraulic conductivity (A), groundwater heads above sea level (L), distance from the sea shore (D), impact of the present position of seawater intrusion (I), and thickness of the aquifer (T).

The effect of seawater intrusion is characterized by the weight of every factor, which varies from 1 to 4. Furthermore, to every factor was allocated a numeric rating from the lowest to the highest vulnerability with values of: 2.5, 5, 7.5, or 10 (table 1).

To assess the seawater intrusion vulnerability index the raster calculator of ArcGIS was employed using the following equation:

\[
\text{GALDIT} \text{ Index} = \frac{\sum_{i=1}^{6} (W_i \cdot R_i)}{\sum_{i=1}^{6} W_i}
\]

where R is the rating and W is the weight. Finally, the GALDIT vulnerability index was split in three different classes: high (>7.5), moderate (5 to 7.5) and low vulnerability (<5).

Increasing GALDIT values means that groundwater contamination potential increase and concomitantly the vulnerability of the aquifer to seawater intrusion also increase.
Table 1. Range and ratings of the six GALDIT parameters.

| Factor                                      | Weight | Factor variable                  | Rating |
|---------------------------------------------|--------|----------------------------------|--------|
| Groundwater occurrence/aquifer type (G)     | 1      | Confined aquifer                 | 10     |
|                                             |        | Unconfined aquifer               | 7.5    |
|                                             |        | Leaky confined aquifer           | 5      |
|                                             |        | Bounded aquifer                  | 2.5    |
| Aquifer hydraulic conductivity (m/day) (A)   | 3      | High                             | >40    |
|                                             |        | Medium                           | 40-10  |
|                                             |        | Low                              | 10-5   |
|                                             |        | Very low                         | <5     |
| Groundwater level above sea level (m) (L)   | 4      | High                             | <1.0   |
|                                             |        | Medium                           | 1.0–1.5|
|                                             |        | Low                              | 1.5–2.0|
|                                             |        | Very low                         | >2.0   |
| Distance from the shore (m) (D)             | 4      | High                             | <500   |
|                                             |        | Medium                           | 500–750|
|                                             |        | Low                              | 750–1000|
|                                             |        | Very low                         | >1000  |
| Impact of the existing status of seawater intrusion (I) | 1 | High                             | >2     |
|                                             |        | Medium                           | 1.5–2.0|
|                                             |        | Low                              | 1.0–1.5|
|                                             |        | Very low                         | <1     |
| Thickness of the aquifer (m) (T)            | 2      | High                             | >10    |
|                                             |        | Medium                           | 7.5–10 |
|                                             |        | Low                              | 5–7.5  |
|                                             |        | Very low                         | <5     |

4. Result and Discussion

The GALDIT methodology was implemented in the littoral area of the Sarti basin in the year 2017 to evaluate the coastal aquifer’s vulnerability to actual seawater intrusion. The thematic maps of GALDIT method are presented in figure 2. The porous aquifer is in both confined and unconfined conditions nearby the coastline and in the margin with the granodiorite. According to the method, the highest values correspond to confined conditions due to the greater capture zone during pumping. K is higher in the margins of the porous aquifer where gravels dominates, whilst nearby the coastline sand and clay render significantly lower values of K. Seawater intrusion is driven by the piezometric conditions of the coastal aquifer. Indisputably, groundwater heads above sea level (L) represents a key parameter, with the highest weight between the other parameters. The highest rating corresponds to piezometric head lower than 1 m. A zone of 600 m towards inland in the central part of the aquifer is characterized by the highest rating of the parameter L, as a result of the negative piezometric head due to over pumping. The existing status of the aquifer is expressed by the Revelle ratio [14]. However, in the studied aquifer it is not representative because the highest values are in the western part due to the low values of HCO3, while the impacted boreholes nearby the sea were eliminated from the supply network and the access to collect groundwater sample was impossible. This might be a drawback of the method in such cases. The path of seawater intrusion is directed from the coastline towards the mainland. Hence, the distance from the shore is a critical parameter and was considered using the multi-buffer zone instrument of ArcGIS and is shown in the thematic map of figure 2. The last parameter is the thickness of the aquifer, where values above 10 m is rated with the highest value. However, the thickness of the studied aquifer is more than 10 m throughout this territory. It is worth to mention that a future modification in the class range of this parameter in the studied aquifer might
increase the vulnerability discretization. Similarly, the existing status of the aquifer might be studied using different ionic ration. Figure 3 shows the final map created applying the GALDIT method as discussed in the previous chapters.

**Figure 2.** Thematic maps of GALDIT method parameters applied to the Sarti coastal aquifer. Starting from the upper left panel, the parameters: G, A, L, D, I and T are reported. See table 1 for explanation.

**Figure 3.** Groundwater vulnerability to seawater intrusion from the of GALDIT method applied to the study area.
Table 2. Distribution of the vulnerability classes (%) according to GALDIT.

| GALDIT score | Vulnerability | km² | %  |
|--------------|---------------|-----|----|
| ≥7.5         | High          | 0.01| 0.5|
| 5 -7.5       | Medium        | 1.51| 76.6|
| <5           | Low           | 0.45| 22.9|

The elevated vulnerability zone represents the 22.9% of the studied aquifer with widths ranging from 40 to 550 m proceeding inland. The remaining portion of the aquifer is categorized by medium vulnerability to seawater intrusion (77%), while a negligible part is categorized by low vulnerability to seawater intrusion (table 2). The final vulnerability map is in agreement with the hydrogeological system of the coastal aquifer of Sarti. The prevailing groundwater management practices, which is characterized by over pumping of groundwater during the summer period usually causes large drawdown inducing negative piezometric heads, and hence has reversed groundwater flow from the coast towards inland. According to Kazakis et al [9] in the high vulnerable zones a detailed monitoring plan should be applied in the coastal aquifer of Sarti, while the pumping rate should be reduced. Recharge of the aquifer using the surplus surface water during winter time will reinforce groundwater reserves. Nevertheless, the excessive water demands during the summer period cannot be covered even if an optimal management plan will be achieved. It is critically important to exploit the surplus surface waters during the winter period by applying artificial recharge in the aquifer and store significant quantities of water in surface reservoirs. The type of reservoirs should be carefully suggested in order to maintain the attractive environment of the area for tourists. It is obvious, from the previous analysis, that only a groundwater vulnerability map to seawater intrusion cannot protect the quality of the aquifer even if all the suggested measures are adopted by local authorities. GALDIT methodology offers a good preliminary screening but it is not able to discriminate all sources of salinization. The main problem of the site is the required amount of water during the summer period. However, exploitation of surface waters should be carefully considered balancing impacts and benefits. A DPSIR analysis could be implemented for the study area in terms of environmental and touristic development sustainability. Additionally, a hydrogeochemical analysis should be also performed in the porous aquifer as well as in the granodioritic fissured rock aquifer and in its springs. Since the need for readily applicable methodologies to protect groundwater resources from seawater intrusion is often stringent, water resources managers have tried to develop many methods to define which areas are more vulnerable. The GALDIT methodology is one of the most used [15]. The above mentioned methodology has been modified with the incorporation of groundwater quality and seawater intrusion events [16]. In this way, the vulnerability mapping could in principle deliver a holistic approach of the examined area’s state, using hydrogeological parameters easily accessible in GIS environment. Nevertheless, it cannot give a clear picture of pollutants’ loads and groundwater contamination of the investigated area. A combination of both methodologies for vulnerability assessment and saltwater intrusion assessment could be considered in future studies as an efficient tool for groundwater management, but it should be complemented with groundwater quality analyses widely distributed in the area, condition not always met in many coastal aquifers [17].

5. Conclusions
The GALDIT method was applied to evaluate the actual seawater intrusion in the coastal area of Sarti. The final map highlights that the littoral part of the aquifer suffers of an elevated seawater intrusion vulnerability, instead the rest of the area has a moderate vulnerability. Some parameters, like groundwater level and distance from the shore, are the ones with higher magnitude; while the existing state of the aquifer, resulted to be a weaker index. The overexploitation of groundwater resources throughout the summer could represent the main problem even if an optimal management plan will be adopted. It is critical to use the water surplus during the winter period by applying artificial recharge in
the aquifer and store significant quantities in the subsurface in order to make it available during the tourist season and to avoid losses due to evaporation. More analysis could be applied in the area like hydrogeochemical analyses in the porous aquifer as well as in the granodioritic fissured rock aquifer and an evaluation of all the possible impacts induced by anthropic activities in order to perform a better management plan.

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