Assessing coastal aquifer vulnerability to seawater intrusion using the "GALDIT" method: Application to the Dradère-Souiere coastal aquifer (Northern Morocco)

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Abstract: In terms of land-use planning, and in an attempt to anticipate and preserve what can be preserved, the prevention of salinization of coastal aquifers is an important step to which researchers are devoting more and more effort, notably by studying their vulnerability to seawater intrusion. GALDIT is a method for "index mapping" the vulnerability of coastal aquifers, dedicated to the risks of seawater intrusion. The present study involves assessing and mapping the vulnerability of the Dradère-Souiere coastal aquifer (Northern Morocco) to seawater intrusion using this method.

Keywords: coastal groundwater; Dradère-Souiere; GALDIT; seawater intrusion; vulnerability.

1 Introduction*

On a global scale, coastal areas occupy just 5% of the world's surface area, demographic projections predict that over 75% of the world's population will live there by 2035 [1]. Population growth in these coastal areas goes hand in hand with high water consumption. Indeed, the inadequacy of surface water resources and their temporal irregularity in these areas encourages local populations to exploit underground resources, often without any real awareness of their vulnerability to seawater intrusion. The salinization of coastal aquifers is becoming a source of concern that requires universal attention, affecting coastal regions that are often densely populated and heavily dependent on groundwater [2], and particularly in arid to semi-arid coastal zones. Under natural conditions, groundwater flows to the sea via the existing natural hydraulic gradient [3]. Over time, however, the overexploitation of groundwater is causing a decline in the hydraulic load of freshwater [4,5]. In addition, the secular rise in sea level associated with climate change [6] leads to an increase in seawater load. This combined effect leads to a breakdown in the hydrostatic balance between freshwater and seawater in coastal areas. This imbalance is reflected in the advance of seawater into the aquifer, often leading to significant degradation of the freshwater resource. This phenomenon is known as seawater intrusion [7].

Faced with this alarming situation, and in terms of land-use planning that is tolerable for the underground environment, several researchers have studied coastal aquifers to assess their vulnerability to marine intrusion. The notion of groundwater vulnerability was first introduced by MARGAT in the 1960s [8]. Vulnerability was subsequently defined as the absence of "natural protection against pollution" [9]. In other words, an area is said to be vulnerable if a pollutant reaches the water table in a very short time and in high concentration, exceeding drinking water limits [10]. In coastal areas, according to Lobo-Ferreira and Cabral (1991) [11], the vulnerability of groundwater to seawater intrusion is defined as the sensitivity of groundwater quality to the effect of imposed pumping and/or a significant rise in sea level. This vulnerability is determined by the intrinsic characteristics of the water table.

Numerous methods have been developed to assess the vulnerability of groundwater to pollution, as a decision-making tool for anticipating and taking protective measures. GALDIT [12] is a method for "index mapping" the vulnerability of coastal aquifers, dedicated to the risks of seawater intrusion. The Dradère-Souiere plain is part of a large aquifer complex that characterizes the Gharb plain, and which constitutes the natural southward extension of the R'Mel de Larache basin. It is a generalized free aquifer that is locally loaded, mainly with Pliocene lumachelles, fine sands and sandstones, topped by more or less clayey Quaternary sands [13,14,15,16]. This small basin is in contact with the Atlantic Ocean, which constitutes its downstream limit. The present study involves assessing and mapping the vulnerability of this coastal aquifer to seawater intrusion using the GALDIT method.

2 Principle and methodology

Determination of the groundwater vulnerability index to seawater intrusion using the GALDIT method
is based on the weighted sum of six parameters that can influence potential seawater intrusion: Groundwater occurrence (A), Aquifer hydraulic conductivity (A), Depth to groundwater Level above the sea (L), Distance from the shore (D), Impact of existing status of sea water intrusion in the area (I) and Thickness of the aquifer (T). Each parameter is rated with a value from 2.5 (lowest vulnerability) to 10 (highest vulnerability). A subjective weighting between 1 and 4 is assigned to each parameter, considering its relative importance to marine intrusion.

The vulnerability index is given by the following relations:

\[ \text{Indice}_{\text{GALDIT}} = \frac{\sum_{i=1}^{6} W_i N_i}{6} \]  (1)

Where \( W_i \) is the weight given (1 to 4) to each parameter. \( N_i \) is the rank or rating given to each parameter (2.5 to 10). The final index can be divided into three classes: low vulnerability (< 5), moderate vulnerability (5-7.5) and high vulnerability (> 7.5).

### Table 1: Summary of weights and ranks for the GALDIT method.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Weight</th>
<th>Classes &amp; Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Very Low</td>
</tr>
<tr>
<td>G</td>
<td>1</td>
<td>Bounded Aquifer</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>&lt;5</td>
</tr>
<tr>
<td>L</td>
<td>4</td>
<td>&gt;2</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>T</td>
<td>2</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

Considering the weights and scores proposed above, the minimum value of the GALDIT index is 2.5 and the maximum value is 10.

### 3 Results and discussion

#### 3.1 Application to the Dradère - Souière coastal aquifer (northern Morocco)

Groundwater piezometry is analysed on the basis of the map drawn up with measurements taken in March 2023 by Sebou Hydraulic Basin Agency (ABHS)(Fig 2).

By calculating the GALDIT index and superimposing the various layers of information using the Geographic Information System (GIS) (Fig 2), we have obtained a vulnerability map that identifies the areas most likely to be significantly affected by seawater intrusion (Fig 3).

#### 3.2 Discussion

Mapping the vulnerability of the Dradère-Souière coastal aquifer to seawater intrusion using the GALDIT method, shows that degrees of vulnerability decrease from the west to the east of the plain, with a high degree of vulnerability in the downstream sector, mainly along the coastal strip, with indices above 7.5. The central and upstream sectors are less vulnerable to seawater intrusion. This high vulnerability of the
downstream sector can be explained firstly by the proximity of the shoreline and the lithological nature of the coastal strip with sandy dunes characterized by high hydraulic conductivity, and secondly by the overexploitation of the water table for agricultural irrigation in the Moulay Bousselham area and along the Atlantic edge, in addition to the effect of the Merja Zerga lagoon.

4 Conclusion

Mapping potential vulnerability to marine intrusion using the GALDIT method is a tool for managing coastal groundwater resources. In this sense, the present study consists in assessing and mapping the vulnerability of the Dradère -Souiere coastal aquifer (Northern Morocco) to seawater intrusion using the GALDIT method. The final map of the GALDIT index shows a wide spatial variability in the degree of vulnerability, increasing towards the sea, with a high risk of contamination in the coastal strip and in the vicinity of the Merja Zerga lagoon. However, the central and amant sector is less vulnerable due to changes in the lithology and hydrodynamic characteristics of the aquifer system.

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