Water in Celtic Countries: Quantity, Quality and Climate Variability (Proceedings of the Fourth InterCeltic Colloquium on Hydrology and Management of Water Resources, Guimarães, Portugal, July 2005).
IAHS Publ. 310, 2007.

Assessing aquifer vulnerability to seawater intrusion using GALDIT method: Part 2—GALDIT Indicators Description

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Abstract This paper is Part 2 of a paper submitted to the 4th InterCeltic Colloquium as Lobo-Ferreira *et al.* (2007). In this second part of the paper the method for assessing GALDIT index parameters is fully explained. The original development of the GALDIT index was done in the framework of the EU-India INCO-DEV COASTIN project, aimed at the assessment of aquifer vulnerability to seawater intrusion in coastal aquifers. The most important factors controlling seawater intrusion were found to be the following: **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 shoreline); **I**mpact of existing status of seawater intrusion in the area; and **T**hickness of the aquifer, which is being mapped. The acronym GALDIT is formed from the highlighted letters of the parameters for ease of reference. These factors, in combination, are found to include the basic requirements needed to assess the general seawater intrusion potential of each hydrogeological setting. GALDIT factors represent measurable parameters for which data are generally available from a variety of sources without detailed examination. A numerical ranking system to assess seawater intrusion potential in hydrogeological settings has been devised using GALDIT factors. The system contains three significant parts: weights, ranges, and ratings. Each GALDIT factor has been evaluated with respect to the other to determine the relative importance of each factor. In this part we also present the first applications of the method developed for the Bardez aquifer in Goa, India.

Key words aquifer vulnerability; groundwater protection; modelling; seawater intrusion

GALDIT—AN OPEN ENDED MODEL

The system presented hereinafter allows the user to determine a numeric value for any hydro-geophysical setting by using an additive model. This model is an open-ended model, allowing for addition and deletion of one or more indicators. However, under normal circumstances, the present set of indicators should not be deleted and any addition of the indicator would require re-deriving of the weights and the classification table.

Factors	Weights
1. Groundwater occurrence (aquifer type)	1
2. Aquifer hydraulic conductivity	3
3. Height of groundwater level above sea level	4
4. Distance from the shore	4
5. Impact of existing status of seawater intrusion	1
6. Thickness of aquifer being mapped	2

INDICATOR DESCRIPTIONS

Groundwater occurrence (aquifer type)

In nature, groundwater generally occurs in geological layers, and these layers may be confined, unconfined, leaky confined or limited by one or more boundaries. The extent of seawater intrusion is dependent on this basic nature of groundwater occurrence. For example, an unconfined aquifer under natural conditions would be more affected by seawater intrusion compared to a confined aquifer as the confined aquifer is under more than atmospheric pressure. Similarly, a confined aquifer may be more prone to seawater intrusion compared to leaky confined aquifer, as the leaky confined aquifer maintains minimum hydraulic pressure by way of leakages from adjoining aquifers. Therefore, in assigning the relative weights to GALDIT parameter **G** one should carefully study the disposition and type of the aquifers in the study area. The confined aquifer is more vulnerable due to its larger cone of depression and instantaneous release of water to wells during pumping and hence scores the high rating. In the case of a multiple aquifer system, the highest rating may be adopted. For example, if an area has all the three aquifers then the rating of 10 of a confined aquifer may be chosen. Table 1 gives the ratings for different hydrogeological conditions.

The data related to groundwater occurrence/type of aquifers can be obtained from analysis of pumping test data and/or lithological logs.

Aquifer hydraulic conductivity

The parameter aquifer hydraulic conductivity is used to measure the rate of flow of water in the aquifer and hence to the sea. By definition, the aquifer hydraulic conductivity is the ability of the aquifer to transmit water. The hydraulic conductivity is the result of the interconnected pores (effective porosity) in the sediments and

Table 1 Ratings for different hydrogeological conditions, parameter **G**.

Indicator	Weight	Indicator variables	Importance rating
Groundwater occurrence/ Aquifer type	1	Confined aquifer	10
		Unconfined aquifer	7.5
		Leaky confined aquifer	5
		Bounded aquifer (recharge and/or impervious boundary aligned parallel to the coast)	2.5

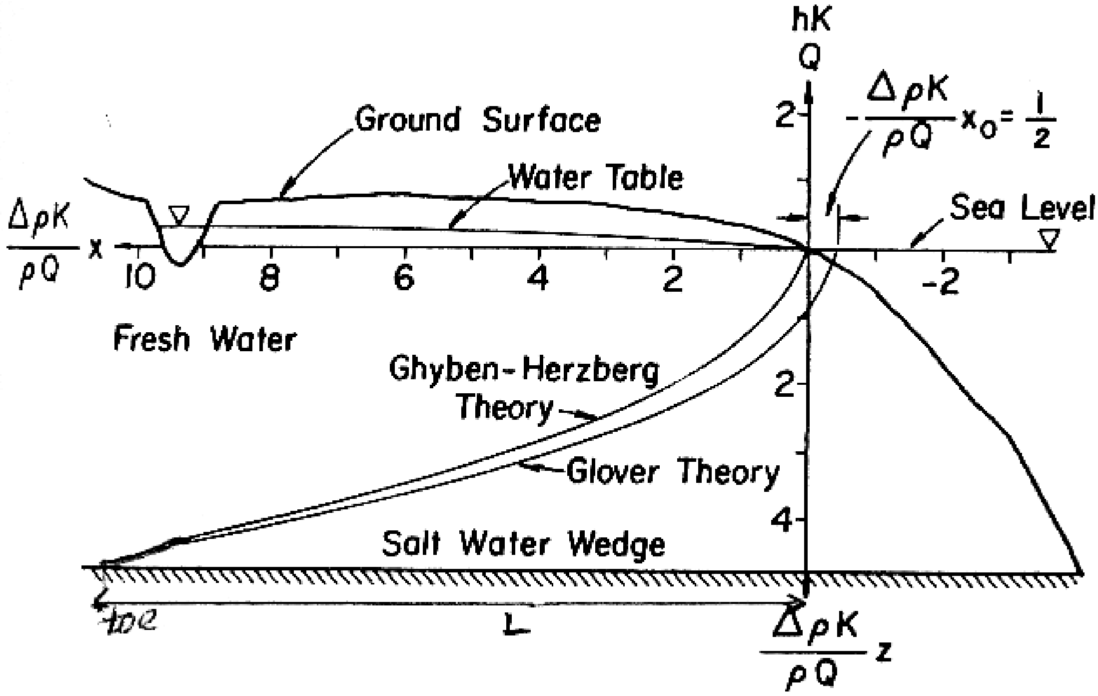

Fig. 1 Length of seawater intrusion toe-l in the coastal aquifer.

fractures in the consolidated rocks. The magnitude of seawater front movement is influenced by the hydraulic conductivity of the aquifer. The higher the conductivity, the greater the inland movement of the seawater front. The high conductivity also results in a wider cone of depression during pumping. In this case, the user should take into account any hydraulic barriers like clay layers, and impervious dykes parallel to the coast, which may act as walls to seawater intrusion.

A relationship exists between the extent of seawater intrusion length (L) and the flow of fresh groundwater to the sea (q) (Fig. 1). The flow of freshwater to the sea is the difference between the natural recharge (W) to the aquifer and the total withdrawal. According to Bear & Verrujit (1987), the equations governing the length (L) of seawater interface for confined and unconfined aquifer are given by:

For confined aquifer:

$$L = KB^2 / 2q\ (\delta) \text{ for } L > B \qquad (1)$$

where, K is the aquifer hydraulic conductivity, B is the saturated aquifer thickness, and δ is given by:

$\delta = \{\rho_{freshwater}/[\rho_{seawater} - \rho_{freshwater}]\} \approx 40$, where ρ is the density of water

For an unconfined aquifer:

$$q = [KB^2/2L].\ [(1 + \delta)/\delta^2] - WL/2$$

where W is the natural recharge.

Seawater intrusion is predominant especially during the non-rainy season when the rainfall recharge is nil. Therefore, for $W = 0$ the above relation reduces to:

$$q = [KB^2/2L].\ [(1 + \delta)/\delta^2]$$

or

$$L = [KB^2/2q].\ 0.0257 \quad (2)$$

By substituting identical values of *K*, *B*, and *q* in equations (1) and (2) the length (*L*) of the computed seawater toe would be nearly identical. The ratings for the GALDIT parameter A, which are modified from Aller *et al* (1987), are shown in Table 2.

Table-2 Ratings for GALDIT parameter *A*.

Indicator	Weight	Indicator variables Class	Range	Importance rating
Aquifer hydraulic conductivity (m day^{-1})	3	High	>40	10
		Medium	10–40	7.5
		Low	5–10	5
		Very low	<5	2.5

The aquifer hydraulic conductivity can estimated from pumping test data as well as from lithological logs.

Height of groundwater level above sea level

The level of groundwater with respect to mean sea elevation is a very important factor in the evaluation of seawater intrusion in an area, primarily because it determines the hydraulic pressure availability to push back the seawater front. As seen from the Ghyben-Herzberg relationship, for every metre of freshwater stored above mean sea elevation, 40 m of freshwater are stored below it down to the interface. In other words, if the groundwater levels are held constant, the change in sea level can cause the same effect. When the sea level is raised the amount of freshwater outflow *q* to sea reduces as shown in equations (1) and (2), and hence the length *L* of the seawater interface increases.

In assigning, the ratings to the GALDIT parameter *L* one should look into the temporal long-term variation of the groundwater levels in the area. Generally, the values pertaining to minimum groundwater levels above sea level may be considered, as this would provide the highest possible vulnerability risk. The ratings adopted for *L* are shown in Table 3.

Table 3 Ratings for GALDIT parameter *L*.

Indicator	Weight	Indicator variables Class	Range	Importance rating
Height of ground water level above msl (m)	4	High	<1.0	10
		Medium	1.0–1.5	7.5
		Low	1.5–2.0	5
		Very low	>2.0	2.5

Table 4 General guidelines for rating of the GALDIT parameter *D*.

Indicator	Weight	Indicator variables		Importance rating
		Class	Range	
Distance from shore / high tide (m)	4	Very small	<500	10
		Small	500-750	7.5
		Medium	750-1000	5
		Far	>1000	2.5

The groundwater level data with respect to mean sea elevation can be obtained by establishing the observation wells in the area.

Distance from the shore

The impact of seawater intrusion generally decreases as one moves inland at right angles to the shore and the creek. The maximum impact is witnessed close to the coast and creek. Table 4 provides the general guidelines for rating of the GALDIT parameter *D* assuming the aquifer is under undisturbed conditions.

Data for this parameter can be computed using the topographical map of the area wherein the high-tide line for the coast has been demarcated.

Impact of existing status of seawater intrusion

If the area under mapping is invariably under stress and this stress has already modified the natural hydraulic balance between seawater and fresh groundwater, this fact should be considered while mapping the aquifer vulnerability to seawater intrusion. Chachadi & Lobo-Ferreira (2001) recommended the ratio of Cl^- / $[HCO_3^{-1} + CO_3^{2-}]$ as another criterion to evaluate seawater intrusion into coastal aquifers. Chloride is the dominant ion in the seawater and it is only available in small quantities in groundwater, while bicarbonate, which is available in large quantities in groundwater, occurs only in very small quantities in seawater. This ratio can be used while assigning the rating for the GALDIT parameter *I*, if the chemical analysis data is available for the area under investigation. If such chemical data is not readily available, then information gathered from the field and water users can be substituted in this rating. Table 5 shows the ratings given for *I* to take care of such field situations.

Table 5 for GALDIT parameter *I*.

Indicator	Weight	Indicator variables		Importance rating based on Cl^- / $[HCO_3^-1 + CO_3^{2-}]$, ratio of groundwater
		Class	Range of Cl^- / $[HCO_3^{-1} + CO_3^{2-}]$, ratio in epm in groundwater	
Impact status of existing seawater intrusion	1	High	>2	10
		Medium	1.5–2.0	7.5
		Low	1–1.5	5
		Very low	<1	2.5

The information required for the above rating can be gathered from historical reports, from the local people, and chemical analysis data.

Thickness of aquifer being mapped

Aquifer thickness or saturated thickness of an unconfined aquifer plays an important role in determining the extent and magnitude of seawater intrusion in coastal areas. It is well established as in equations (1) and (2) that the larger the aquifer thickness the larger the extent of seawater intrusion and *vice versa*. Keeping this as a guideline the following ratings are given for various ranges of aquifer thickness (Table 6).

Table 6 Ratings for various ranges of aquifer thickness.

Indicator	Weight	Indicator variables		Importance rating based on the saturated aquifer thickness
		Class	Range	
Aquifer thickness (saturated) in metres	2	Large	>10	10
		Medium	7.5–10	7.5
		Small	5–7.5	5
		Very small	<5	2.5

The aquifer thickness in a given area can be obtained from lithological logs and can be deduced from carefully conducted vertical electrical sounding data.

COMPUTING THE GALDIT INDEX

Each of the six indicators has a pre-determined fixed weight that reflects its relative importance to seawater intrusion. The GALDIT Index is then obtained by computing the individual indicator scores and summing them as per the following expression:

$$\text{GALDIT-Index} = \sum_{i=1}^{6} \{(W_i).R_i\} / \sum_{i=1}^{6} W_i \qquad (3)$$

where W_i is the weight of the ith indicator and R_i is the importance rating of the ith indicator.

Thus, the user can use hydrogeological and geological information from the area of interest and choose variables to reflect specific conditions within that area, choose corresponding importance ratings, and compute the indicator score. This system allows the user to determine a numerical value for any hydro-geographical setting by using this additive model. The "maximum GALDIT-Index" is obtained by substituting the maximum importance ratings of the indicators as shown below:

$$\text{Max} = \{(1)*R_1 + (3)*R_2 + (4)*R_3 + (4)*R_4 + (1)*R_5 + (2)*R_6\} / \sum W_i$$

$i = 1$

$= \{(1)*10 + (3)*10 + (4)*10 + (4)*10 + (1)*10 + (2)*10\}/15$

$= 10$ (4)

Similarly, the "minimum GALDIT-Index" is obtained by substituting the minimum importance ratings of the indicators as shown below:

$\text{Min} = \{(1)*R_1 + (3)*R_2 + (4)*R_3 + (4)*R_4 + (1)*R_5 + (2)*R6\}/ \sum W_i$

$i = 1$

$= \{(1)*2.5 + (3)* 2.5 + (4)* 2.5 + (4)* 2.5 + (1)* 2.5 + (2)* 2.5/15$

$= 2.5$ (5)

Therefore, the minimum and maximum GALDIT-Index varies between 2.5 to 10. The vulnerability of the area to seawater intrusion is assessed based on the magnitude of the GALDIT Index. In a general way, the lower the index the less vulnerable it is to seawater intrusion.

DECISION CRITERIA

Once the GALDIT-Index has been computed, it is then possible to classify the coastal areas into various categories of seawater intrusion vulnerability. The range of minimum and maximum GALDIT-Index scores (i.e. 2.5–10) is divided into three groups as shown in Table 7. All the six indicators have 2.5, 5, 7.5, and 10 as their importance ratings. Table 7 provides the detailed classification as derived from Table 8.

Table 7 Vulnerability classes.

Sr. no.	GALDIT-Index Range	Vulnerability classes
1	≥7.5	Highly vulnerability
2	5–7.5	Moderately vulnerability
3	<5	Low vulnerability

Table 8 Computation of GALDIT index.

S. no.	Indicator	Weight	Range of importance ratings				Range of score (weight importance)		
			Min.	In between		Max.	Min	In between	
1	**G**roundwater occurrence (aquifer type)	1	2.5	5	7.5	10	2.5	5	7.5
2	**A**quifer hydraulic conductivity	3	2.5	5	7.5	10	7.5	15	22.5
3	Depth to groundwater **L**evel above sea	4	2.5	5	7.5	10	10	20	30
4	**D**istance from the shore	4	2.5	5	7.5	10	10	20	30
5	**I**mpact of existing status of seawater intrusion	1	2.5	5	7.5	10	2.5	5	7.5
6	**T**hickness of aquifer being mapped	2	2.5	5	7.5	10	5	10	15
						Total score (T.S)	37.5	75	112
						GALDIT-Index = T.S/15	2.5	5	7.5

APPLICATION OF THE GALDIT METHOD TO A CASE STUDY AREA IN GOA, INDIA

The above method has been validated using a case study in the coastal area of North Goa (Fig. 2). The GALDIT scores at each of the 56 groundwater monitoring wells were computed for the Goa study area in Bardez Taluk for normal sea level conditions. These GALDIT values along with the *x* and *y* co-ordinates were used in the SURFER package to draw the vulnerability contour map. The map derived for this study area is given in Fig. 2.

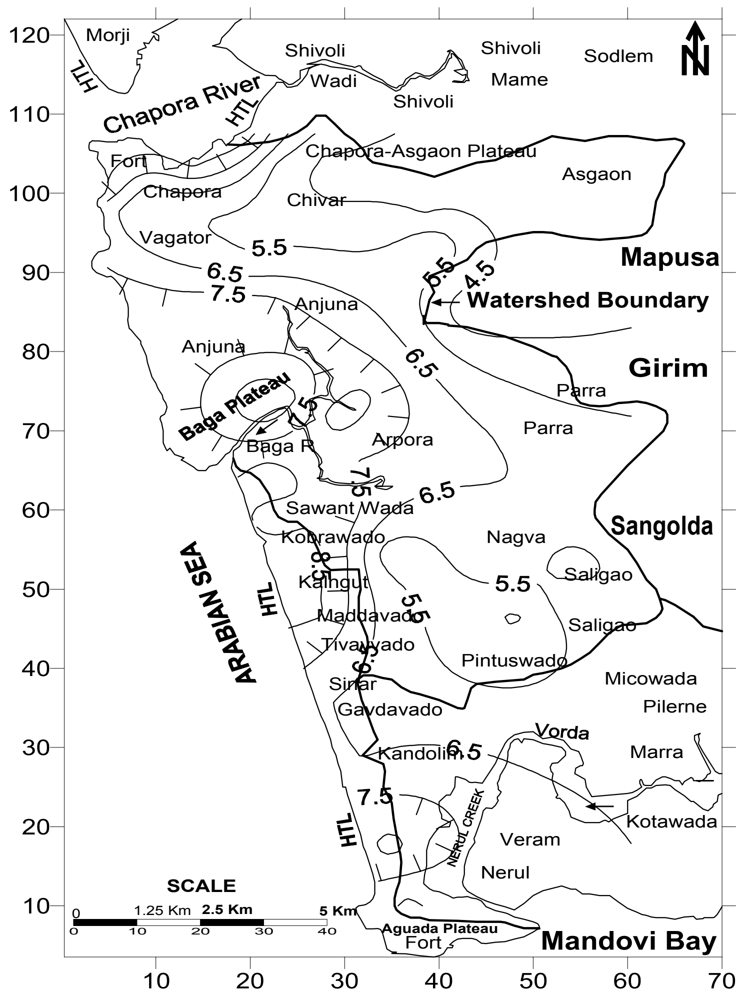

Fig. 2 Location and GALDIT score map of the study area in North Goa, India.

A former application of the GALDIT Index to the Bardez aquifer in Goa, India, is available at http://www.teriin.org/teri-wr/coastin/newslett/coastin4.pdf and at http://-www.teriin.org/teri-wr/coastin/newslett/coastin7.pdf. Figure 3 shows results computed with a former version of GALDIT Index (as described in the two abovementioned pdf files) allowing the comparison between GALDIT scores for normal and raised sea levels on the North Goa coast.

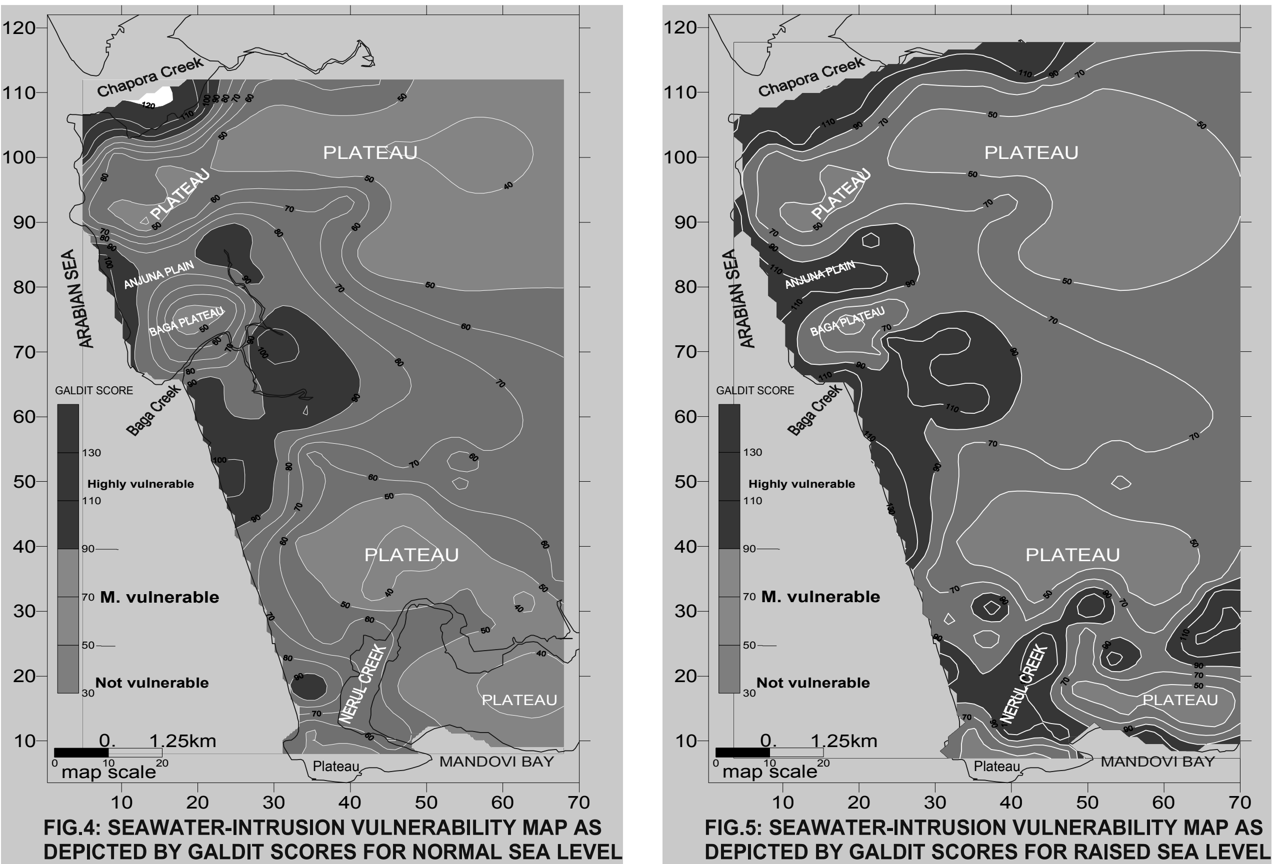

Fig. 3 Comparison between GALDIT scores for normal and raised sea levels in North Goa coast (left figure for normal sea level and right figure for raised sea level).

Acknowledgements We acknowledge the European Commission, Laboratório Nacional de Engenharia Civil, in Portugal, and Goa University, in India, for partially supporting the groundwater component of COASTIN Project (INCO-DC contract no. IC18-CT98-0296—Final report available at http://www.dha.lnec.pt/nas/estudos/-COASTIN.htm).

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