Assessing aquifer vulnerability to sea-water intrusion using GALDIT method: Part 2 – GALDIT Indicators Description

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Abstract This paper is Part 2 of the paper submitted to this 4th Interceltic Colloquium as LOBO-FERREIRA *et al.* (2005). In this second part of the paper the method for assessing GALDIT index parameters is fully explained. The original development of GALDIT index was done in the framework of the EU-India INCO-DEV COASTIN project aiming the assessment of aquifer vulnerability to sea-water 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 sea water 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 determined to include the basic requirements needed to assess the general seawater intrusion potential of each hydrogeologic 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 hydrogeologic 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, sea water intrusion, modeling, groundwater protection

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 circumstance, 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. **G**roundwater Occurrence (Aquifer Type)	**1**
2. **A**quifer Hydraulic Conductivity	**3**
3. Height of Groundwater **L**evel above Sea Level	**4**
4. **D**istance from the Shore	**4**
5. **I**mpact of existing status of Seawater Intrusion	**1**
6. **T**hickness of Aquifer being Mapped	**2**

INDICATOR DESCRIPTIONS

Groundwater Occurrence (Aquifer Type)

In nature, groundwater generally occurs in the 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 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 larger cone of depression and instantaneous release of water to wells during pumping and hence scores the high rating. In case of multiple aquifer system in an area, 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. The following Table-1 gives the ratings for different hydrogeological conditions:

Table 1 - Ratings for parameter Groundwater occurrence/Aquifer type

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**

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

There exist a relation 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 and VERRUJIT (1987), the equations governing the length (L) of seawater interface for confined and unconfined aquifer are given by,

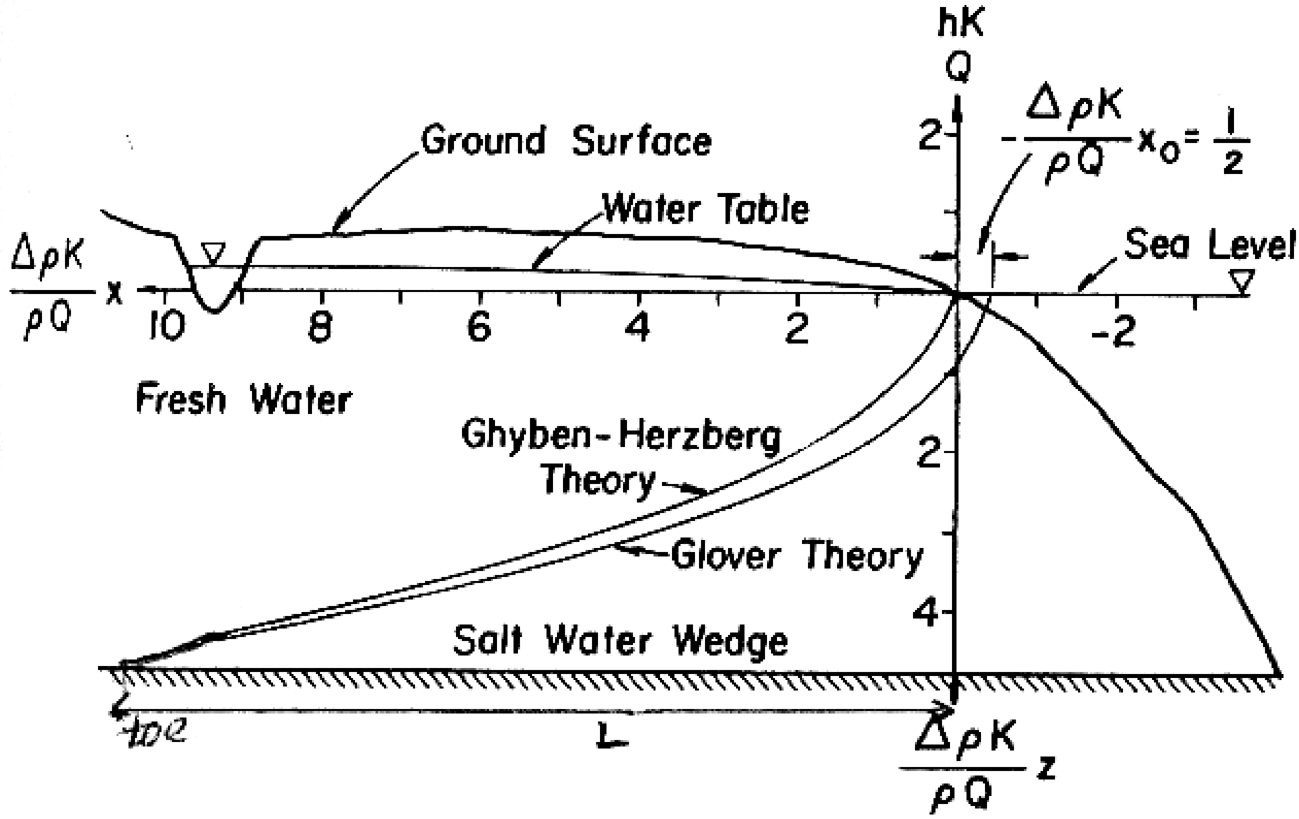

Fig. 1: Length of seawater intrusion toe- l in the coastal aquifer

For Confined Aquifer

$L = KB^2 / 2q\ (\delta)$ for $L > B$, **(1)**

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

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

For Unconfined Aquifer

$q = [KB^2/2L].\ [(1+\delta)/\delta^2] - WL/2$, where W is the natural recharge.

The 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 $L = [KB^2/2q]\ .\ 0.0257$ **(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 as below:

Table 2 - Ratings for parameter Aquifer Hydraulic Conductivity

Indicator	Weight	Indicator Variables		Importance Rating
		Class	**Range**	
Aquifer Hydraulic Conductivity (m/day)	**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 the 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 relation, for every meter of fresh water stored above mean sea elevation, 40 meters 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 fresh water outflow q to sea reduces as shown in equations (1) and (2) and hence the length L the seawater interface toes 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 may be considered, as this would provide the highest possible vulnerability risk. The ratings adopted for L are as below:

Table 3 - Ratings for parameter Height of Groundwater Level above Sea Level

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
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**

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 move inland at right angles to the shore and the creek. The maximum impact is witnessed close to the coast and creek. The following table provides the general guidelines for rating of the GALDIT parameter **D** assuming the aquifer is under undisturbed conditions;

Table 4 - Ratings for parameter Distance from shore / High Tide

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**

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 and LOBO-FERREIRA (2001) recommended the ratio of Cl^- / [HCO_3^{-1} + CO_3^{2-}] as another criterion to evaluate seawater intrusion into the 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. In case such chemical data is not readily available then information gathered from the field and water users can be infused in this rating. The following ratings are given for I to take care of such field situations:

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

Table 5 - Ratings for parameter Impact status of existing seawater intrusion

Indicator	Weight	Indicator Variables		Importance Rating based on Cl^- / $[HCO_3^{-1} + CO_3^{2-}]$, ratio of ground water
		Class	Range of Cl^- / $[HCO_3^{-1} + CO_3^{2-}]$, ratio in epm in ground water	
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**

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 the coastal areas. It is well established as per equations (1) and (2) that larger the aquifer thickness 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 - Ratings for parameter Aquifer thickness (saturated)

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:

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

Where W_i is the weight of the i^{th} indicator and R_i is the importance rating of the i^{th} indicator.

Thus, the user can use hydrogeologic 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:

$$\mathbf{Max} = \{(1)*R_1 + (3)*R_2 + (4)*R_3 + (4)*R_4 + (1)*R_5 + (2)*R_6\} / \sum_{i=1}^{6} W_i$$

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

$$= 10 \qquad (4)$$

Similarly,

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

$$\text{Min} = \{(1)*R_1 + (3)*R_2 + (4)*R_3 + (4)*R_4 + (1)*R_5 + (2)*R6\}/ \sum_{i=1}^{6} W_i$$

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

$$= 2.5 \qquad (5)$$

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, lower the index less vulnerable to seawater intrusion.

DECISION CRITERIA

Once the GALDIT-Index has been computed, it is therefore 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 to 10) is divided into 3 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.

Table7 - GALDIT Vulnerability classes

Sr. no.	GALDIT-Index Range	VULNERABILITY CLASSES
1	≥ 7.5	Highly vulnerability
2	5 to 7.5	Moderately vulnerability
3	< 5	Low Vulnerability

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

The above method has been validated using 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 existing sea level. 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.

Table8 - Computation of GALDIT Index

Computation of GALDIT-Index

S.no.	Indicator	Weight	Range of importance ratings				Range of scores (weight*Importance rating)			
			Minimum	In between		Maximum	Min	In between		Max
1	Groundwater Occurrence (Aquifer Type)	1	2.5	5	7.5	10	2.5	5	7.5	10
2	Aquifer Hydraulic Conductivity	3	2.5	5	7.5	10	7.5	15	22.5	30
3	Depth to Groundwater Level above Sea	4	2.5	5	7.5	10	10	20	30	40
4	Distance from the Shore	4	2.5	5	7.5	10	10	20	30	40
5	Impact of existing status of Seawater Intrusion	1	2.5	5	7.5	10	2.5	5	7.5	10
6	Thickness of Aquifer being Mapped	2	2.5	5	7.5	10	5	10	15	20
				Total Score (T.S)			37.5	75	112.5	150
				GALDIT-Index=T.S/15			**2.5**	**5**	**7.5**	**10**

Note: 15 is the total of all 6 indicator weight

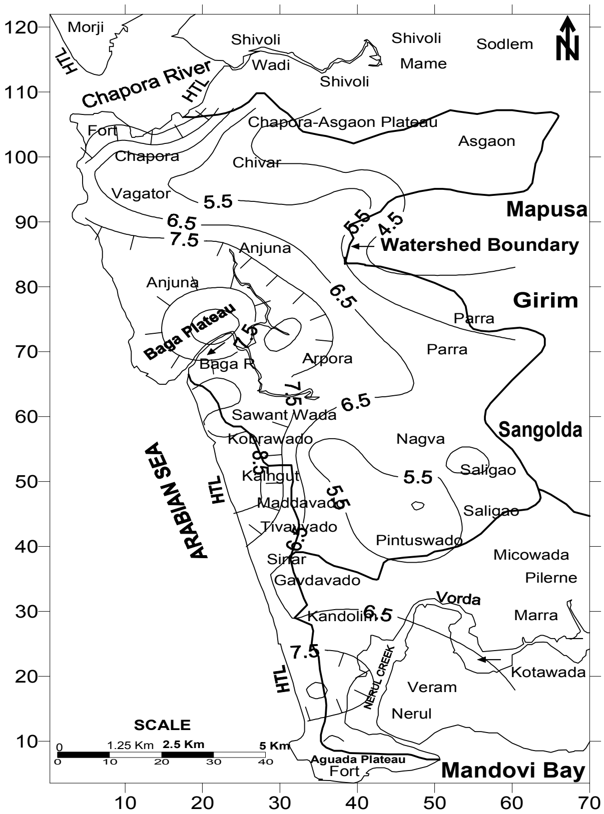

Fig. 2 Location and GALDIT score map of the study area in North Goa, India

A former application of the GALDIT index to the Bardez aquifer in Goa, India, is available in http://www.teriin.org/teri-wr/coastin/newslett/coastin4.pdf and in http://www.teriin.org/teri-wr/coastin/newslett/coastin7.pdf. Fig. 3 shows results computed with a former version of