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SEAWATER INTRUSION MAPPING USING MODIFIED GALDIT INDICATOR MODEL - CASE STUDY IN GOA

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ABSTRACT *An indicator-based model is presented to assess and quantify the vulnerability magnitude of coastal aquifers to seawater intrusion due to excessive groundwater withdrawals or possible rise in the sea level. The new method, GALDIT, of aquifer vulnerability mapping due to seawater intrusion, has been successfully used to assess the extent of aquifer contamination due to seawater intrusion. The maps derived can be used as a tool for management of the coastal groundwater resources. Similar applications can be carried out for the island aquifers so that optimal management practices can be evolved for groundwater use. The paper discusses application details of the model to a region in North Goa.*

Key words Aquifer vulnerability mapping; GALDIT indicator model; vulnerability evaluation; vulnerability ranking.

INTRODUCTION

The Indian coastline stretches over a length of more than 7000 km, covering about 53 coastal districts. The nine maritime states include Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Orissa, and West Bengal besides the union territories of Andaman and Nicobar Islands, Daman, Diu, Lakshadweep, and Pondicherry. Most of the coastal districts in these states and Union Territories have well-developed ports, urban, and industrial establishments. The concentration of mega cities, industries, harbors, farm cultivation, aquaculture, and tourist activities clubbed with high population density have transformed these resource-abundant areas into resource-scarce ones. Both the quality and quantity of all the natural resources are decreasing day by day along the coasts. The stress on freshwater resources is indeed a matter of great concern.

The major portion of the water used for various purposes in the coastal belts comes from groundwater reservoirs. The unplanned extraction and overexploitation of the groundwater resource in the coastal belts has led to alarming situations leading to seawater intrusion and groundwater pollution besides salinisation of fertile agricultural lands in many parts of India. As per Intergovernmental Penal on Climate Change IPCC estimates, a one-meter rise in sea level is expected to inundate about 1700 km^2 of agricultural land in Orissa and West Bengal.

The continuous human interference in the coastal hydrological and hydrogeological regimes has resulted in pollution of the coastal groundwater reservoirs by seawater and anthropogenic wastes. Incidents of groundwater pollution due to seawater intrusions have increased many folds in the past couple of decades. Generally, pollution of groundwater due to mixing of saltwater is realized only after the incident has occurred. Experience shows that the remediation of the groundwater system, which has undergone seawater intrusion, is rather difficult and uneconomical in most cases.

A change in groundwater levels with respect to the mean sea elevation (msl) along the coast largely influences the extent and magnitude of seawater intrusion into the freshwater aquifers. In other words, a rise in sea level would have the same effect on seawater intrusion episode in the coastal aquifers even if the groundwater levels were maintained at certain level above msl. In the geological past due to natural climatic variations, sea levels changed several times along the Indian coast during the glacial and interglacial periods. These changes i.e. rise and falls in sea levels, during the geological past have been well recorded in the form of transgressive (during rising sea levels) and regressive (during falling sea levels) types of sediment deposits. However, in the present time, the climate is largely influenced by human interference, which has led to an imbalance in the atmospheric heat balance. The effect of this thermal imbalance is expected to cause melting of polar ice caps leading to a rise in sea levels (Asthana, 1994). Local sea level rise may also be possible due to the dumping of huge terrestrial sediments into the open sea by rivers

OBJECTIVE

In the present study, the aim is to develop an indicator-based model to assess and quantify the vulnerability magnitude of the coastal aquifers to seawater intrusion due to excessive groundwater withdrawals or possible rise in the sea levels (in the future) or both.

CONCEPT FOR THE DEFINITION OF GROUNDWATER VULNERABILITY TO POLLUTION DUE TO SEAWATER INTRUSION

Before evaluating the vulnerability of groundwater to pollution, it is necessary to define the term vulnerability. The term vulnerability has been defined and used before in the area of water resources, but within the context of system performance evaluation by Hashimoto *et al.* (1982). Here, an analysis of system performance, which focuses on system failure, was presented by defining three concepts that provide useful measures of system performance:

1. How likely the system is to fail is measured by its *reliability*;
2. How quickly the system returns to a satisfactory state once a failure has occurred is expressed by its *resiliency*; and
3. How severe the likely consequences of failure may be is measured by its *vulnerability*.

This concept of vulnerability defined in the context of system performance can also be used in the context of groundwater pollution due to seawater intrusion. The aquifer 'system failure' in the coastal belts would also occur when the 'magnitudes of groundwater extraction or sea level rise or both' are significant factors. The severity of the consequence is measured in terms of water quality deterioration and its aerial extent.

However, the most useful definition of vulnerability is the one that refers to the intrinsic characteristics (physical parameters of the aquifers like permeability, porosity, storativity etc.) of an aquifer, which are relatively static and mostly beyond human control. It is therefore proposed that the groundwater vulnerability due to seawater intrusion be redefined – as 'the sensitivity of coastal groundwater reservoir to seawater intrusion due to an imposed groundwater pumping or sea level rise or both, which is determined by the intrinsic characteristics of the aquifer'.

The risk of pollution due to mixing of seawater depends not only on the vulnerability of an aquifer but also on the existence of significant groundwater extraction, or sea level rise or both in the proximity of the coast. It is also possible to have high aquifer vulnerability with no risk of saltwater intrusion, if there is no significant groundwater extraction, or sea level rise or both in the proximity of the coast. But to have high pollution risk despite low vulnerability, the groundwater extraction has to be exceptionally high and persistent. It is important at this point to make a clear distinction between vulnerability and risk. Not only the intrinsic characteristics of the aquifer, which are relatively static and hardly changeable, but on the existence of dynamic and some controllable activities such as groundwater extraction, or sea level rise or both along the coast determine the risk of seawater intrusion.

Considerations on whether an episode of groundwater pollution due to seawater intrusion will result in a serious threat to groundwater quality and thus to its (already developed or designated) water supply are not included in the proposed definition of vulnerability. The seriousness of the impact on water use will depend not only on aquifer vulnerability to seawater intrusion but also on the magnitude of an episode of intrusion and the importance of the groundwater resource in the area.

METHODOLOGY

Hydrogeological conditions as well as human activities close to the coast mainly affect groundwater quality due to seawater mixing and contamination due to toxic wastes. There has been lack of appropriate methodology to map the spatial distribution of the vulnerable coastal areas to potential seawater intrusion taking into account hydrogeological factors. Therefore, it has been thought necessary to develop a mapping system that is simple enough to apply using the available data, and yet capable of making best use of available data in a technically valid and useful way.

One of the systems for evaluation of vulnerability of aquifer to pollution and ranking include a vulnerability index, which is computed from hydrogeological, topographical, and other aquifer characteristics in a well-defined way. The adoption of an index has the advantage of, in principle, eliminating or minimizing subjectivity in the ranking process. Lobo-Ferreira and Cabral (1991) suggested that a vulnerability index be used in the vulnerability ranking performed for European community maps. Such a standardized index has been adopted and is currently in use in Canada, South Africa, and the USA. The DRASTIC (a seven parameter indicator model) index developed by Aller *et al.* (1987) for the US EPA is one such method, which is simple and useful.

SUGGESTED SYSTEM OF VULNERABILITY EVALUATION AND RANKING

Inherent in each hydrogeologic setting are the physical characteristics that affect the seawater intrusion potential. The most important mappable factors that control the seawater intrusion are found to be:

1. **G**roundwater Occurrence (aquifer type; unconfined, confined and leaky confined).
2. **A**quifer Hydraulic Conductivity.
3. Height of Groundwater **L**evel Above Sea Elevation.
4. **D**istance of the Point in Question From the Shore (distance inland perpendicular from shoreline).
5. **I**mpact Magnitude of the Existing Seawater Intrusion in the Area, if any.
6. **T**hickness of the Aquifer (which is being mapped).

The acronym GALDIT is formed from the highlighted and underlined letters of the factors 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 reconnaissance.

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 *importance ratings*. Each GALDIT factor has been evaluated with respect to the other to determine the *relative importance* of each factor. The basic assumption made in the development of the tool includes: the bottom of the aquifer(s) lies below msl so that the seawater can move inside the aquifer laterally. Any event of seawater moving inland and causing seawater mixing in the freshwater aquifers such as storm surges and tsunamis, which normally move seawater inland by vertical uplift, is not considered in the present model. The various parameters adopted in the evolution of the present indicator tool include:

(i) Identification of all the *indicators* influencing the seawater intrusion episode – This task was achieved through extensive discussions and consultations with the experts, academicians etc.

(ii) Derivation of indicator *weights* – Indicator weights depict the relative importance of the indicator to the process of seawater intrusion. After identifying the indicators, a group of people consisting of geologists, hydrogeologists, environmentalists, students, and in-house experts was asked to weigh these indicators in the order of importance to the process of seawater intrusion. The feedbacks from all such interactions were analyzed statistically and the final consensus list of indicators weights was prepared (Table 1). The most significant indicators have weights of 4 and the least a weight of 1 in a five-point scale indicating parameter of less significance in the process of seawater intrusion. As the indicator weights are derived after elaborate discussions and deliberations among the experts, academicians, researchers, etc., they must be considered as constants and may not be changed under normal circumstances.

(iii) Assigning *importance rates* to indicator variables using a scale of 2.5 to 10 – Each of the indicators is subdivided into variables according to the specified attributes to determine the relative significance of the variable in question on the process of seawater intrusion. The importance ratings range between 2.5, 5, 7.5 and 10. Higher value of importance rating indicates higher vulnerability to seawater intrusion.

(iv) *Decision criterion* – It is the total sum of the individual indicator scores obtained by multiplication of values of *importance ratings* with the corresponding *indicator weights*. Higher the values of importance ratings of the variable, more vulnerable are the aquifers to seawater intrusion.

Table 1 Indicator weights.

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

AN OPEN ENDED MODEL

The system presented here 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 the user 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.

INDICATOR DESCRIPTIONS

Indicator-1: Groundwater Occurrence (Aquifer Type)

Description In nature, groundwater generally occurs in the geological layers and these layers may be confined, unconfined, and 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, compared to confined aquifer, an unconfined aquifer under natural conditions would be more affected by seawater intrusion, since the confined aquifer exists under more 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 compared to other types of aquifers. 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. Table 2 gives the ratings for different hydrogeological conditions.

Table 2 Ratings for different hydrogeological conditions.

Indicator (*G*)	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

Data Availability The data related to groundwater occurrence/type of aquifers can be obtained from analysis of pumping test data and/or lithological logs. The data can also be ascertained from vertical electrical soundings and geological cross sections of the area.

Indicator-2: Aquifer Hydraulic Conductivity

Description The parameter aquifer hydraulic conductivity is used to measure the rate of flow of water in the aquifer and hence to and fro from the sea in the coastal area. 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. For a given hydraulic head, a high value of hydraulic conductivity of an aquifer leads to larger inland movement of the seawater front. The high hydraulic conductivity also results in wider cone of depression during pumping and may allow greater seawater intrusion if located close to the coast. In assigning the importance rating to this factor the user should also 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 exists a relation between the extent of seawater intrusion length (L) and the flow of fresh groundwater to the sea (q) as shown in Fig. 1. The flow of freshwater to the sea is the difference between the natural recharge to the aquifer and the total withdrawal. According to Bear and Verrujit (1987), the

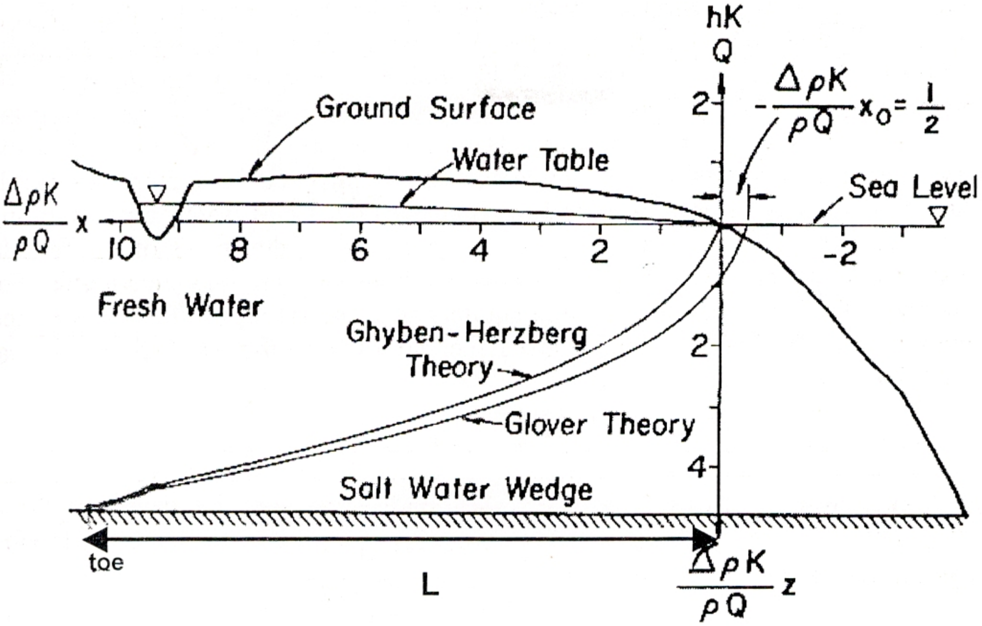

Fig. 1 Length (*L*) of seawater intrusion in the coastal aquifer.

equations governing the length (*L*) of seawater interface for confined and unconfined aquifer are as given below.

For Confined Aquifer

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

where K is the aquifer hydraulic conductivity; B is the saturated aquifer thickness; and δ is defined as $\{\rho_{freshwater} / [\rho_{seawater} - \rho_{freshwater}]\} \approx 40$, where ρ is the density of water.

For Unconfined Aquifer

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

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

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

$$\text{or } L = [KB^2/2q] \times 0.0257 \tag{2}$$

By substituting identical values of K, B, and q in Eqs. (1) and (2), the length (L) of the computed seawater toe would be nearly identical. However, seawater intrusion is directly proportional to hydraulic conductivity in both cases of aquifers. The ratings for the GALDIT parameter A, which are modified from Aller *et al.* (1987), are given in Table 3.

Table 3 Ratings adopted for the GALDIT parameter A.

Indicator (A)	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

Data Availability The aquifer hydraulic conductivity can be estimated from pumping test data as well as from lithological logs. The well log data and porosity logs can also be used to compute the aquifer hydraulic conductivity.

Indicator-3: Height of Groundwater Level Above Sea Elevation

Description The level of groundwater with respect to mean sea elevation is the most 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 famous Ghyben-Herzberg relation, for every meter rise of fresh water above mean sea elevation, a freshwater column of 40 m is developed below it down to the interface and vice-versa. In other words if the groundwater levels are assumed to remain constant then one meter rise in sea level can cause the an effect wherein the freshwater column below the land is reduced by 40 m and vice-versa. When the sea level is raised the amount of fresh water outflow q to sea reduces as shown in Eqs. (1) and (2) and hence the length L of the seawater interface toe increases.

In assigning the ratings to the GALDIT parameter L, the long-term spatial variations of the groundwater levels in the area need to be carefully studied. Generally, the values pertaining to minimum groundwater levels above sea (pre-monsoon during May) may be considered, as this would provide the highest possible vulnerability risk. The ratings adopted for L are given in Table 4.

Table 4 Ratings adopted for the GALDIT parameter L.

Indicator (L)	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

Data Availability Groundwater level data with respect to msl can be obtained by establishing observation wells in the area and measuring the pre- and post-monsoon water levels and reducing them with respect to the mean sea level.

Indicator-4: Distance of the Point in Question From the Shore

Description The magnitude of 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 creeks under favorable hydrogeological conditions. Table 5 provides the general guidelines for rating of the GALDIT parameter *D* assuming the aquifer is under undisturbed conditions i.e. the groundwater development in the area has not been significant to offset the balance. The value of importance ratings is assumed to change linearly with distance *D*.

Table 5 Ratings adopted for the GALDIT parameter *D*.

Indicator (*D*)	Weight	Indicator Variables		Importance Rating
		Class	Range	
Distance of the point in question from shore / High tide (m)	4	Very small	<500	10
		Small	500-750	7.5
		Medium	750-1000	5
		Far	>1000	2.5

Note: Under critical pumping conditions the seawater has intruded several kilometers inland in some parts of Tamil Nadu, Gujarat, A.P., and West Bengal etc.

Data Availability Data for parameter *D* can be computed using the topographical/ cadastral or any surveyed data map of the area wherein the high tide line for the coast has been demarcated.

Indicator-5: Impact of Existing Status of Seawater Intrusion

Description Some times the area under mapping is already under water stress conditions and this stress might have affected the natural hydraulic balance between seawater and fresh groundwater. This existing imbalance in the seawater-freshwater interface should be considered while mapping the aquifer vulnerability to seawater intrusion. Revelle (1941) recommended the ratio of Cl / [HCO_3 + CO_3] as a criteria to identify the extent of seawater intrusion into the coastal aquifers. Chloride (Cl) is the dominant ion in the seawater and it is only available in small quantities in groundwater while bicarbonate (HCO_3), which is available in large quantities in groundwater, occurs only in very small quantities in seawater. This ratio can be used while assigning the importance rating for the GALDIT parameter *I*, provided 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 survey and inquiries from the water users in the area can be used in assigning the importance rating for *I*. Table 6 provides ratings for *I* to take care of such field situations.

Table 6 Ratings adopted for the GALDIT parameter *I*.

Indicator (*I*)	Weight	Indicator Variables		Importance Rating [based on $Cl/(HCO_3+CO_3)$ ratio of groundwater]
		Class	Range of $Cl/(HCO_3+CO_3)$ 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

Note: In the absence of chemical quality data the area can be classified based on field observations as highly, moderately, low and very low seawater intrusion affected area and then assigns the importance ratings accordingly.

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

Indicator-6: Thickness of Aquifer Being Mapped

Description 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 Eqs. (1) and (2), that larger the aquifer thickness, the greater is the extent of seawater intrusion and vice versa. Keeping this as a guideline the ratings given in Table 7 are adopted for various ranges of aquifer thickness *T*.

Table 7 Ratings adopted for the GALDIT parameter *T*.

Indicator (*T*)	Weight	Indicator Variables		Importance Rating [based on 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

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

COMPUTATION OF THE GALDIT INDEX

Each of the six GALDIT indicators has a pre-determined fixed weight that reflects its relative importance to seawater intrusion. Computing the individual indicator scores and summing them and dividing by the total weight as per the following expression gives the GALDIT Index:

$$\text{GALDIT Index} = \sum_{i=1}^{6} \{(W_i)\, R_i\} / \sum_{i=1}^{6} W_i \tag{3}$$

where W_i is weight of the i^{th} indicator and R_i is 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 given below:

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

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

$$= 10 \tag{4}$$

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

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

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

$$= 2.5 \tag{5}$$

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 is the area to the 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. All the six indicators have four classes i.e. 2.5, 5, 7.5, and 10 as their importance ratings. Table 8 provides the detailed classification as derived from Table 9, which gives computation of GALDIT Index.

Table 8 Vulnerability classes.

S. No.	GALDIT Index Range	Vulnerability Classes
1	≥ 7.5	High vulnerability
2	5 to 7.5	Moderate vulnerability
3	< 5	Low vulnerability

Table 9 Computation of GALDIT Index.

S. No.	Indicator	Weight	Range of Importance Ratings				Range of Scores (weight × importance rating)			
			Min.	In between		Max.	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 weights.

APPLICATION OF THE GALDIT MAPPING – CASE STUDY AREA IN GOA COAST

The above method has been validated using case studies in Kakinada coast in Andhra Pradesh, Thane coast in Maharashtra, North Goa coast in Goa and also Atlantic Ocean coast in Southern Portugal. The application details of the model to the North Goa case study area are discussed below.

The present study area (Fig. 2) forms part of the coastal tract of North Goa district spread over about 15 km in length between Fort Aguada in South to Fort

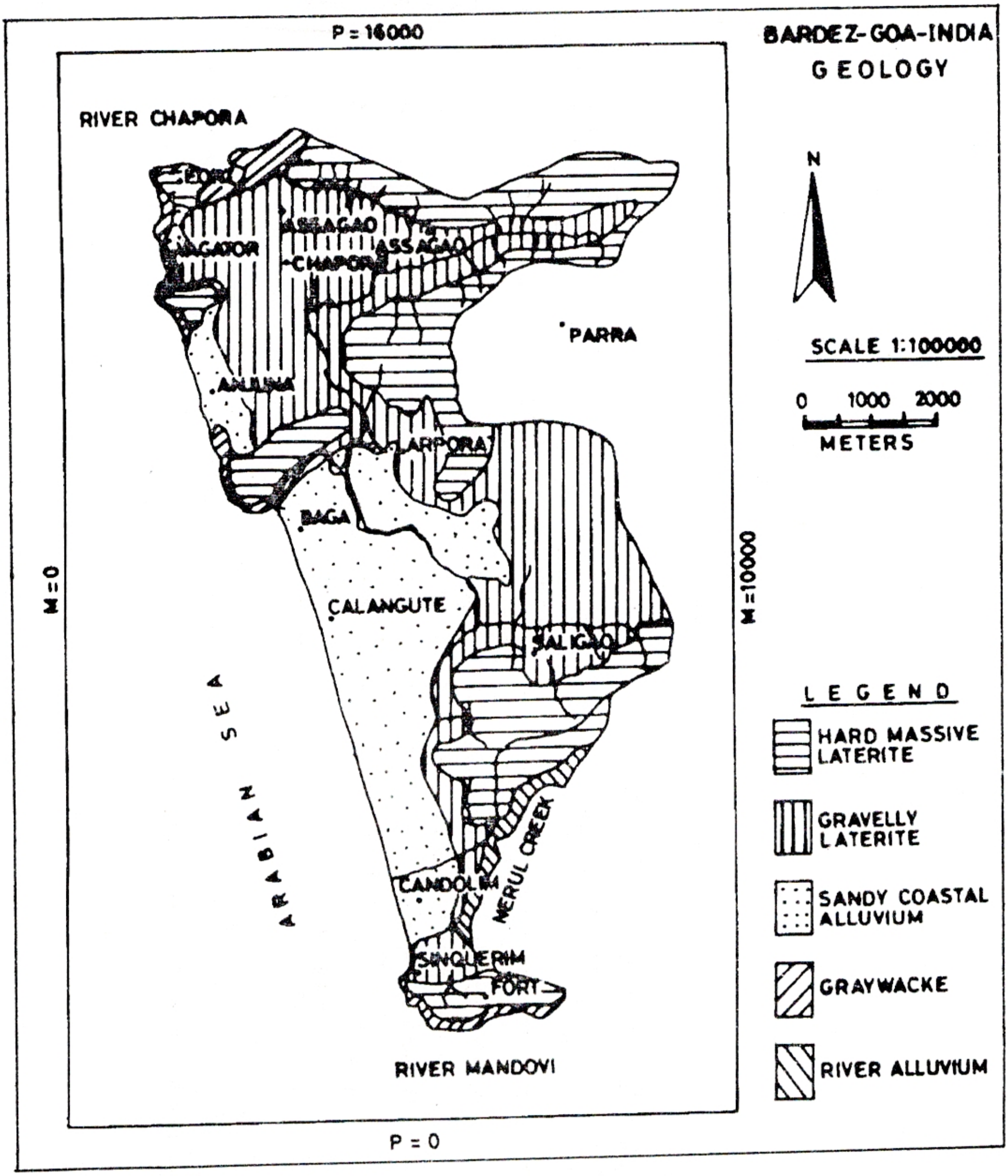

Fig. 2 Geological map of the study area.

Chapora in the North. The Mandovi River Estuary in the South and the Chapora River in the North form the hydrological boundaries of the study area. The geological map along with the location of watershed is also shown in Fig. 2.

The area is mainly covered by laterites and river alluvium and at some places the metasediments are exposed in the north. In the study area 59 groundwater monitoring wells have been established and monthly groundwater levels have been recorded in all these wells for 18 months. The well network in the area is shown in Fig. 3.

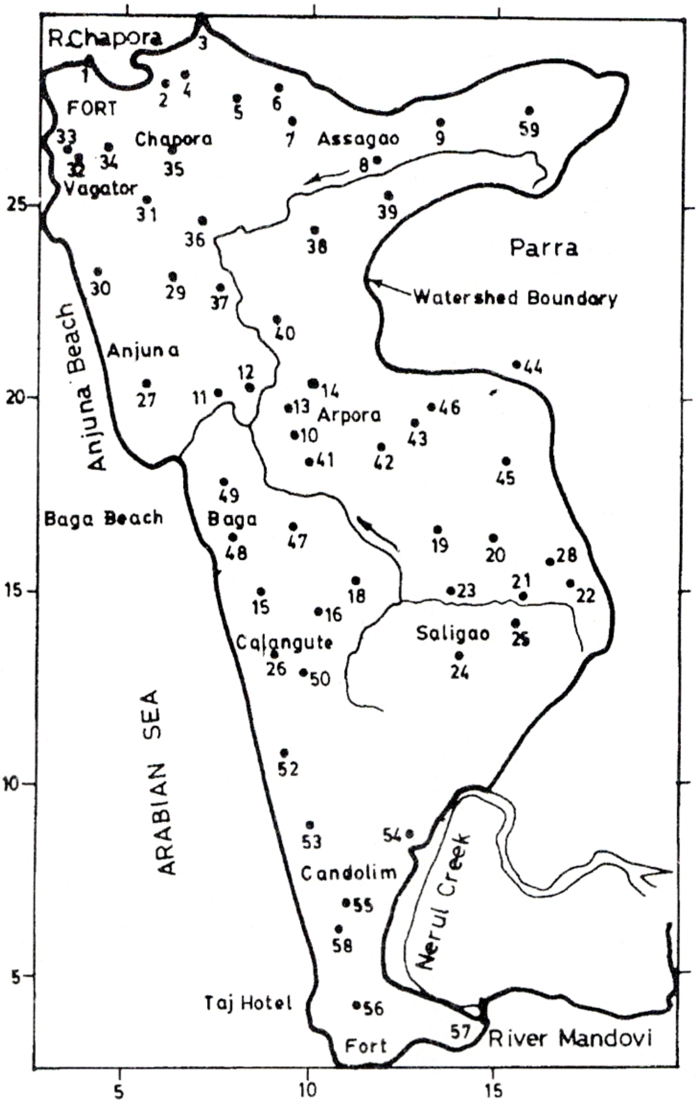

Fig. 3 Location of groundwater monitoring wells in the study area.

A map showing the groundwater flow in pre-monsoon (May) period has been prepared showing the different aspects of groundwater regime in Fig. 4. As seen from the map, the flow direction is in accordance with the general topography of the area. The aquifer is mainly shallow unconfined in nature occurring both in river alluvium as well as laterites exposed in the low lying areas. The plateau laterites generally lack water table and at some places the water table is very deep. The river alluvium is highly drainable whereas the laterites are not.

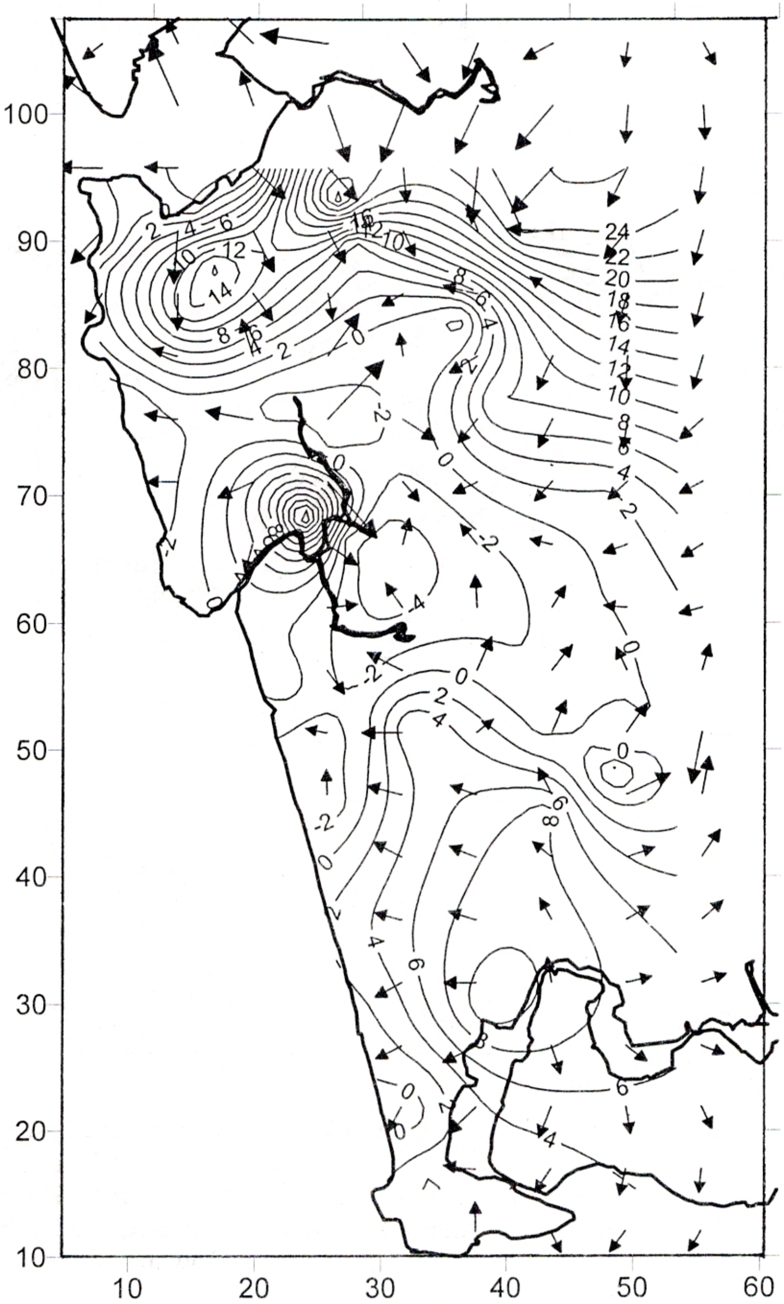

Fig. 4 Map of pre-monsoon groundwater flow in the study area.

The GALDIT scores at each of the 59 groundwater monitoring wells were computed for the study area. 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 shown in Fig. 5.

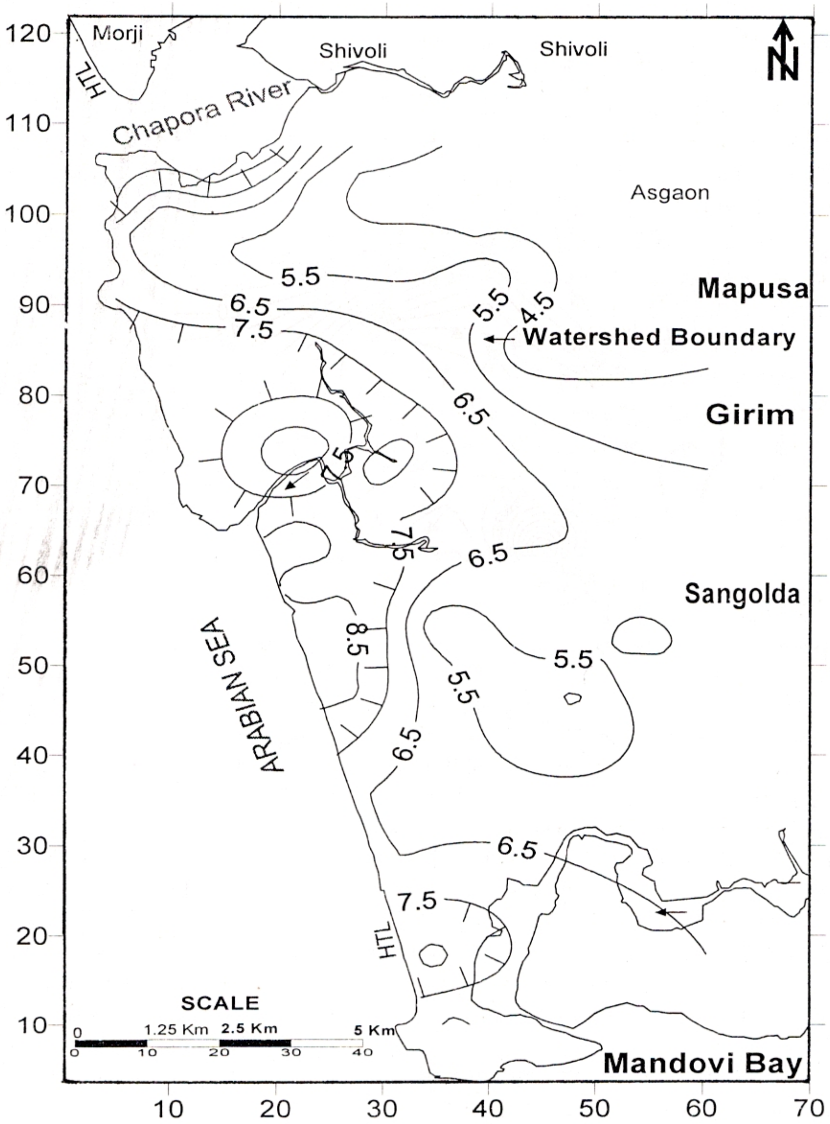

Fig. 5 Seawater intrusion vulnerability magnitude map for North Goa Coast.

From the figure it is seen that the low-lying river alluvium areas and areas in proximity to the creek are highly vulnerable to seawater intrusion. These findings can also be visualized from the pre-monsoon groundwater flow map shown in Fig. 4 wherein the flow lines at places point landward.

CONCLUSIONS

The new method of aquifer vulnerability mapping due to sea water intrusion i.e. GALDIT method developed by Chachadi and Lobo-Ferreira (2001) has been successfully used to assess the extent of aquifer contamination due to sea water intrusion. The maps derived can be used as a tool for management of the coastal groundwater resources. Similar applications can be carried out for the island aquifers so that optimal management practices can be evolved for groundwater use. The maps can be prepared using GIS or if the area is small, point values of the vulnerability indices can be obtained from Eq. (3) and then contoured using SURFER to get a vulnerability score map as done in the present study. The point values of GALDIT index can be used in ascertaining the wellhead protection areas in the coastal belts to prevent seawater mixing. For the cases where the aquifer bottom is above the sea level, all GALDIT parameters should be assigned zero values when using SURFER for preparing the vulnerability maps as this hydrogeological situation does not allow seawater intrusion. This can be taken care of in GIS platform by defining the areas having such hydrogeological situation as a separate layer. The effect of sea level changes on the likely magnitude of seawater intrusion areas can be easily assessed using this model. Besides the likely losses in the land use can be quantified due to a given rise in sea level.

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