Seawater Intrusion Mapping Using Modified GALDIT Indicator Model

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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 (1992) 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 salt water 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 (risen and fallen) several times along the Indian coast during the glacial and interglacial periods. These rise and fall 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.

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, it has been aimed to develop an indicator-based model to assess the vulnerability 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 (Hashimoto, Stedinger, and Loucks 1982).

These authors present an analysis of system performance, which focuses on system failure. They define three concepts that provide useful measures of system performance:

(i) how likely the system is to fail is measured by its **reliability**,
(ii) how quickly the system returns to a satisfactory state once a failure has occurred is expressed by its **resiliency**, and
(iii) 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 salt-water 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 condition 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, morphological, 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 US. The DRASTIC (a seven parameter indicator model) index developed by Aller, Bennett, Lehr, 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 is the physical characteristics that affect the seawater intrusion potential. The most important mappable factors that control the seawater intrusion are found to be;

(i) **G**roundwater Occurrence (aquifer type; unconfined, confined and leaky confined).
(ii) **A**quifer Hydraulic Conductivity.
(iii) Height of Groundwater **L**evel above Sea Level.
(iv) **D**istance from the Shore (distance inland perpendicular from shoreline).
(v) **I**mpact of existing status of seawater intrusion in the area.
(vi) **T**hickness of the aquifer, which is being mapped.

The acronym **GALDIT** is formed from the highlighted and underlined 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 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 include: that the bottom of the aquifer(s) lies below the mean sea level.

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) 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, 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. The most significant indicators have weights of **4** and the least a weight of **1** 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 of ***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 and 10. Higher importance rating indicates high vulnerability to seawater intrusion.

(iv) **Decision criterion:** 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.

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 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

INDICATOR-1: Groundwater Occurrence (Aquifer Type)

Description:

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 hydrogeological conditions

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

Data Availability

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

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 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,

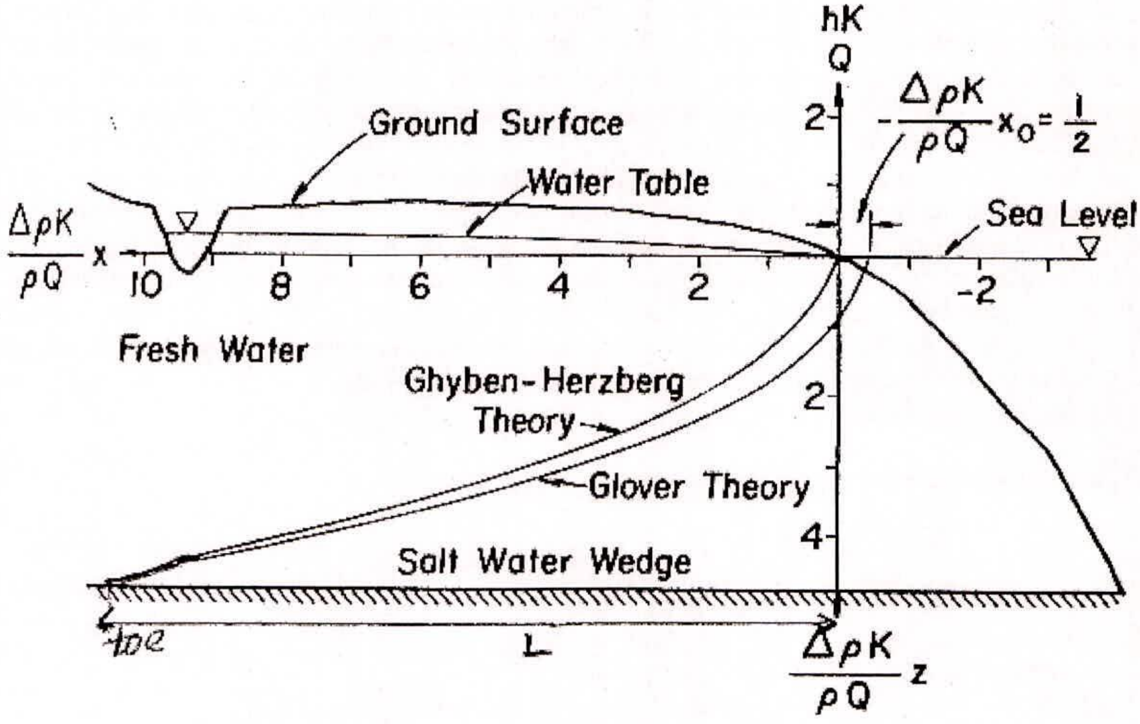

Fig. 1 Length of seawater intrusion toe - L in the coastal aquifer

1) 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 given by

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

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

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 A

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

Data Availability:

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

INDICATOR-3: Height of Groundwater **L**evel above Sea Level

<u>Description:</u>

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 (Premonsoon) 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 L

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

Data Availability:

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

INDICATOR-4: Distance from the Shore

Description:

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 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

Data Availability:

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.

INDICATOR-5: Impact of existing status of Seawater Intrusion

Description:

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.

Revelle (1941) recommended the ratio of Cl / [HCO_3 + CO_3] as another criteria 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:

Table 5 Ratings for parameter I

Indicator	Weight	Indicator Variables		Importance Rating based on $Cl/(HCO_3+CO_3)$ ratio of ground water
		Class	Range of $Cl/(HCO_3+CO_3)$ 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

Data Availability:

The information required for the above rating can be gathered from historical reports, inquiry from the local people, 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 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 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

Data Availability:

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 OF 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:

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

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:

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

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

Similarly,

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

$$\text{Min} = \{(1)^*R_1 + (3)^*R_2 + (4)^*R_3 + (4)^*R_4 + (1)^*R_5 + (2)^*R6\} / \sum_{i=1}^{6} W_i$$
$$= \{(1)^*2.5 + (3)^* 2.5 + (4)^* 2.5 + (4)^* 2.5 + (1)^* 2.5 + (2)^* 2.5/15$$
$$= 2.5 \quad (5)$$

Therefore, the minimum and maximum MPR 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 8. 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

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

Table 8 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 sum of all 6 indicator weights

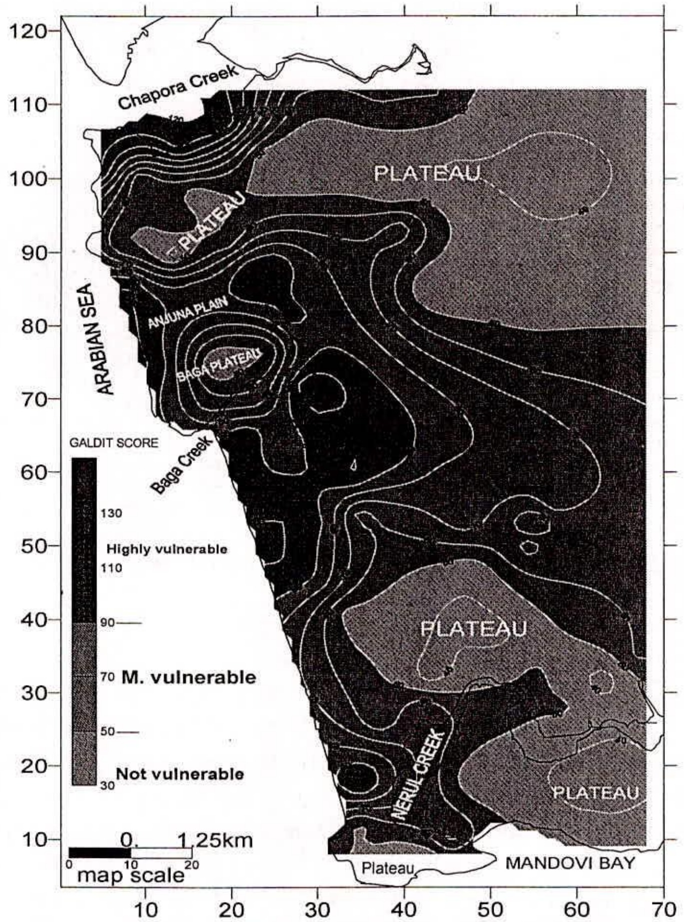

Fig. 4 Seawater intrusion vulnerability map as depicted by GALDIT scores for normal sea level

APPLICATION OF THE GALDIT MAPPING – CASE STUDY AREA IN GOA

The above method has been validated using case study in the coastal area of North Goa. 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 maps derived for this study area is given in Figs. 4 and 5.

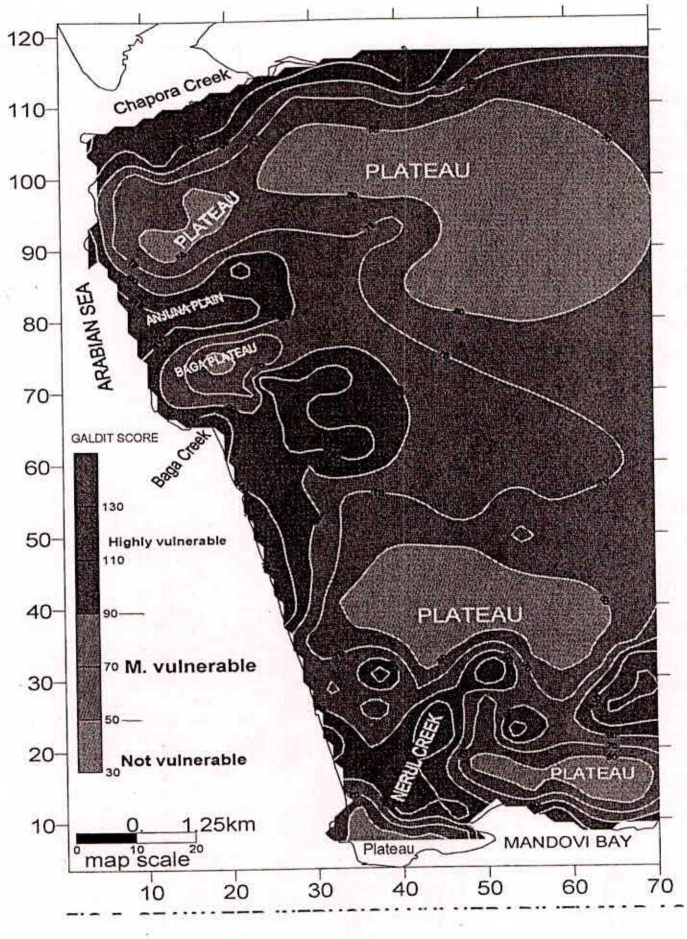

Fig. 5 Seawater intrusion vulnerability map as depicted by GALDIT scores for raised sea level

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 made use 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 done 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 equation (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 the SURFER for preparing the vulnerability maps as this hydrogeological situation does not allow seawater intrusion. This can be taken care in GIS platform by defining the areas having such hydrogeological situation as a separate layer.

REFERENCES

Andersen, L.J. and Gosk, E. (1987). Applicability of vulnerability maps, in W. van Duijvanbooden and H.G. van Waegeningh (eds.), Vulnerability of Soil and Groundwater to Pollution, Proceedings and Information No. 38 of the International Conference held in the Netherlands, in 1987, TNO Committee on Hydrological Research, Delft, The Netherlands.

Aller, L., Bennett, T., Lehr, J.H. and Petty, R. J. (1987). DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings, U.S. EPA Report 600/2-85/018.

Asthana,V. (1994). Impacts of green house-induced sea level rise on the islands and the coasts of India. New Delhi: Jawaharlal Nehru University.

Chachadi, A.G. and Ferreira, L. (2001). Sea water intrusion vulnerability mapping of aquifers isung GALDIT method. Proc. Workshop on modeling in hydrogeology, Anna University, Chennai, pp.143-156.

Duijvenbooden, W. van and Waegeningh, H.G. van (1987). Vulnerability of Soil and Groundwater to Pollutants, Proceedings and Information No. 38 of the International Conference held in the Netherlands, in 1987, TNO Committee on Hydrological Research, Delft, The Netherlands.

Foster, S.S.D. (1987). Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy, in W. van Duijvanbooden and H.G. van Waegeningh (eds.), Vulnerability of Soil and Groundwater to Pollution, Proceedings and Information No. 38 of the International Conference held in the Netherlands, in 1987, TNO Committee on Hydrological Research, Delft, The Netherlands.

Hashimoto, T., Stedinger, J. R. and Loucks, D. P. (1982). Reliability, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation, Water Resources Research, 18(1), p14-20.

Lobo-Ferreira, J.P. and Cabral, M. (1991). Proposal for an Operational Definition of Vulnerability for the European Community's Atlas of Groundwater Resources, in Meeting of the European Institute for Water, Groundwater Work Group Brussels, Feb. 1991.

Marothia, D.K. (1997). Agricultural technology and environmental quality: an institutional perspective. Indian Journal of Agricultural Economics 52(3): 473-487.

Pachauri,R.K. and Batra, R.K. eds. (2001). Climate change. Directions, innovations, and strategies of harnessing action for sustainable development, Green India 2047, Tata Energy research Institute, ISBN 81-85419-80-9. pp.63-74.

TERI (1999). Measuring, monitoring, and managing sustainability: the coastal dimension. First year progress report of the INCO-DC Project contract No. IC18-CT98-0296.

UNEP (1998), Convention on climate change. Bonn, Germany:Climate change secretariate. 30pp.

Vaidyanathan, A. (1996). Depletion of ground water: some issues. Indian Journal of Agricultural Economics 51(1-2), pp.184-19.