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Assessing aquifer vulnerability to seawater intrusion using the GALDIT method: part 1—application to the Portuguese Monte Gordo aquifer

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Abstract This paper is divided into two parts. Part 1 presents the first application in Europe of an index developed in the framework of the EU-India INCO-DEV COASTIN project that aims to assess coastal aquifer vulnerability to seawater intrusion. The most important factors controlling seawater intrusion were found to be: **G**roundwater occurrence (aquifer type; unconfined, confined and leaky confined); **A**quifer hydraulic conductivity; height of groundwater **L**evel above the sea level; **D**istance from the shore (distance inland perpendicular from shoreline); **I**mpact of existing status of seawater intrusion in the area; and the **T**hickness of the aquifer that is being mapped. The acronym GALDIT is formed from the highlighted letters of the parameters for ease of reference. These factors, in combination, were 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 application of the method is exemplified in the paper for the assessment of aquifer vulnerability to seawater intrusion in Portugal (Monte Gordo aquifer in the Portuguese southern Algarve region). The system contains three significant parts: weights, ranges, and ratings. Each GALDIT factor has been evaluated with respect to the others to determine their relative importance. In Part 2 of the paper the method for assessing GALDIT index parameters is fully explained.

Key words aquifer vulnerability; groundwater protection; modelling; sea water intrusion

PROBLEM DEFINITION

Continued human interference with the coastal hydrological systems has led to pollution of coastal groundwater aquifers by salt water. The incidence of groundwater pollution due to salt-water intrusion has increased manifold in the last two decades.

Change in groundwater levels with respect to mean sea elevation along the coast largely influences the extent of seawater intrusion into fresh water aquifers. The smaller the drop in groundwater levels, the less the seawater intrusion into the aquifers. In other words, the magnitude of change in sea level would have the identical effect on seawater intrusion if the groundwater levels were held constant. In the geological past, sea levels have changed with changes in natural climatic conditions several times. This happened during the glacial and interglacial periods, which are well recorded by coastal sediments in the form of transgressive and regressive sediment types. However, in the geological present, the climate is largely influenced by human interference in the form of air and water pollution, and this has led to an imbalance in atmospheric heat. The effect of this thermal imbalance is seen in the melting of polar ice caps leading to a rise in sea level. Coastal infrastructure, tourism, and other economic activities such as oil exploration are also at risk. Tourism in coastal areas is largely dependent on the availability of beaches; if sea levels rise, these beaches are subjected to submergence and morphological changes, besides damaging the infrastructural facilities close to the coast.

The aim of the present investigation is to study the impacts of sea level rise on the extent of surface inundation along the coast and seawater intrusion into the coastal aquifers in southern Portugal's Algarve coastal zone, comparing it to the study developed for North Goa coast, making use of the GALDIT method developed by Chachadi & Lobo-Ferreira (2001) and presented in Chachadi & Lobo-Ferreira (2007).

DEFINITION OF GROUNDWATER VULNERABILITY TO SEAWATER INTRUSION

Following the basics concepts presented in Lobo-Ferreira & Cabral (1991) for the definition of groundwater vulnerability to pollution, we believe that the most useful definition of vulnerability to seawater intrusion is one that refers to the intrinsic characteristics of the aquifer, which are relatively static and mostly beyond human control. It is, therefore, proposed that groundwater vulnerability to seawater intrusion be defined as: *the sensitivity of groundwater quality to an imposed groundwater pumpage or sea level rise or both in the coastal belt, which is determined by the intrinsic characteristics of the aquifer.*

SUGGESTED SYSTEM OF VULNERABILITY EVALUATION AND RANKING

GALDIT index

Inherent in each hydrogeological 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:

- **G**roundwater occurrence (aquifer type; unconfined, confined and leaky confined).
- **A**quifer hydraulic conductivity.
- Height of groundwater **L**evel above Sea Level.
- **D**istance from the shore (distance inland perpendicular from shoreline).
- **I**mpact of existing status of seawater intrusion in the area.
- **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 is 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:

Identification of all the indicators influencing the seawater intrusion episode This task was achieved through extensive discussions and consultations with the experts, academics, etc.

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 feedback from all such interactions was analysed 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 a 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.

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.

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 values of importance ratings of the variable, correspond to more vulnerable aquifers to seawater intrusion.

Due to the limited number of pages available for this publication it is not possible to place all the methodology of GALDIT index assessment in this paper. The methodology is, however, easy to obtain if the reader refers to Part 2 of this paper, i.e. Chachadi & Lobo-Ferreira (2007), also published in the Proceedings of this 4th InterCeltic Colloquium. 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 http://www.teriin.org/teri-wr/coastin/newslett/coastin7.pdf and is presented in the second Part of this paper, i.e. Chachadi & Lobo-Ferreira (2007).

GALDIT APPLICATION TO THE AQUIFER SYSTEM OF MONTE GORDO

The limits of the aquifer system of Monte Gordo have been defined by INAG (1997). It is an unconfined porous aquifer, extending from Vila Real de Santo António, in southern Portugal's Algarve region, to Praia Verde, having an extension of about 5 km long by 2 km average width, occupying a total area of approximately 10 km^2 (Silva, 1984). Concerning its lithological formation, this aquifer system is formed of sands located along the coast line in a narrow strip of sand dunes reaching more than 10 m in thickness. This is an environment protected area occupied by pine trees. To the north of this region, one finds sands of different grain sizes with important argillaceous and organic components, corresponding to old dune systems and alluvial materials (Silva, 1984). According to this author, the structure of the aquifer system corresponds to an E–W basin, overlying an impermeable substratum constituting of silts and clays, of unknown thickness, considered as old alluviums. Underlying this level, coloured Pliocene sandstone appears. The saturated zone corresponds to a sand level with a thickness estimated to be 12 m; at the surface a sand dune system occurs, the thickness of which depends on the topography, sometimes exceeding 10 m. According to several geologic profiles published by Silva (1984), the impermeable substratum is practically horizontal with a slight inclination towards the south.

The limits of the aquifer system are: in the north, the Carrasqueira River, in the south, the Atlantic Ocean, in the west, the argillaceous sandstone of the Pliocene and, in the east, the Guadiana River estuary. Figure 1 shows the hydrogeological map of the study area, where the inventoried wells have been represented.

From the hydrogeological viewpoint, Monte Gordo is an unconfined aquifer, with about 12 m of saturated thickness. The covering sand dunes do not exceed 10 m in thickness. Figure 2 shows a N–S conceptual cross-section of the aquifer where one can observe the above-mentioned formations and the existence of two saltwater–freshwater

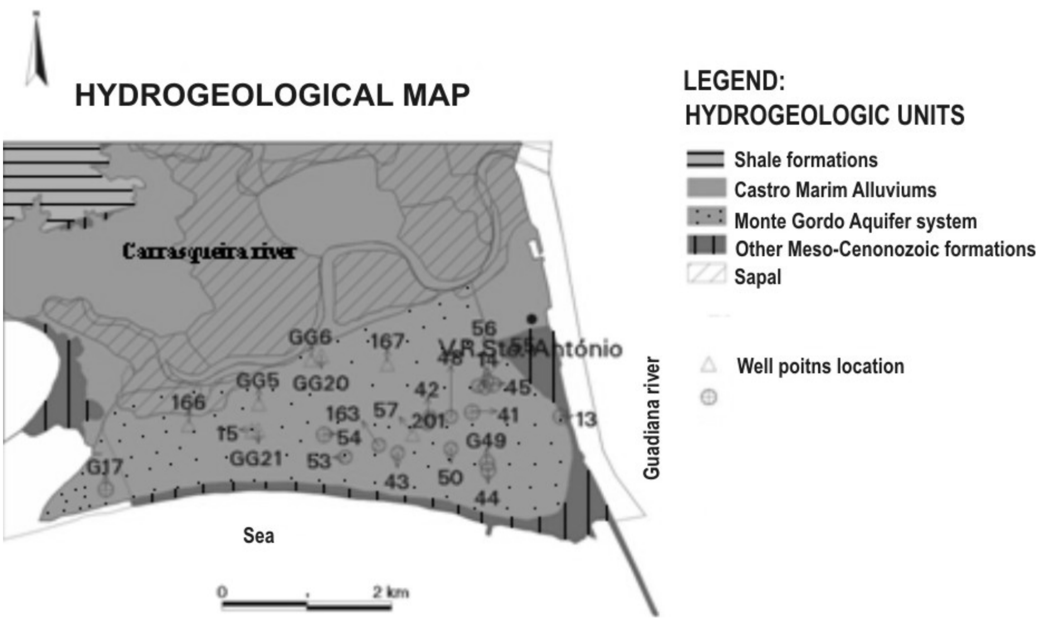

Fig. 1 Hydrogeological map of the aquifer system of Monte Gordo.

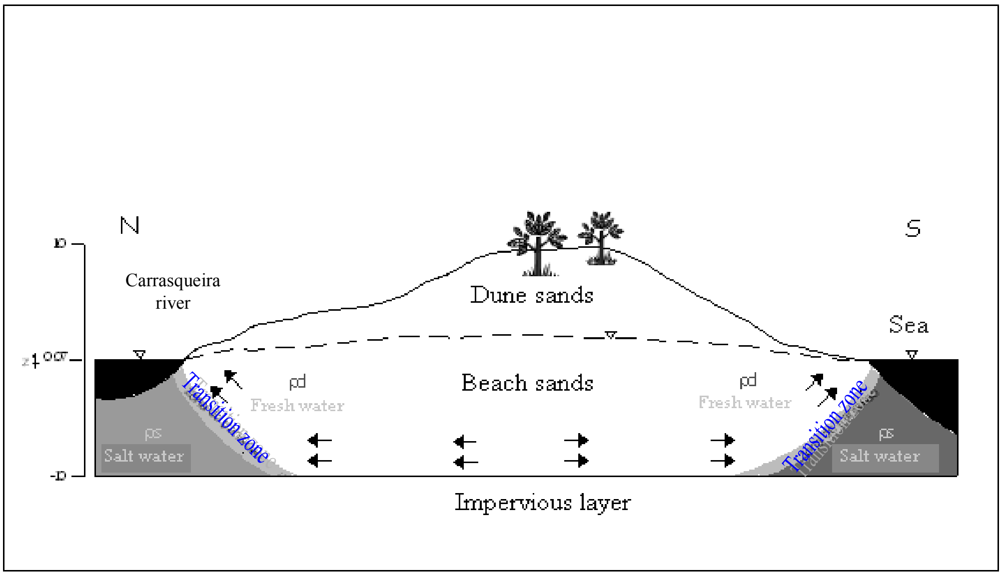

Fig. 2 N-S conceptual cross-section of the aquifer system of Monte Gordo.

interfaces, one along the Carrasqueira River and the other along the coastal zone. On the ocean side the salt water content is about 36 g L^{-1}, therefore high salinity content. On the side of both the Carrasqueira and Guadiana rivers we have considered a brackish water zone, with a lower salinity of about 5 g L^{-1}.

For application to the Monte Gordo aquifer system the six GALDIT parameters were evaluated

Parameter G: groundwater occurrence (aquifer type) The aquifer system of Monte Gordo is an unconfined aquifer so a GALDIT rating for this parameter G of 7.5 was assigned (Fig. 3).

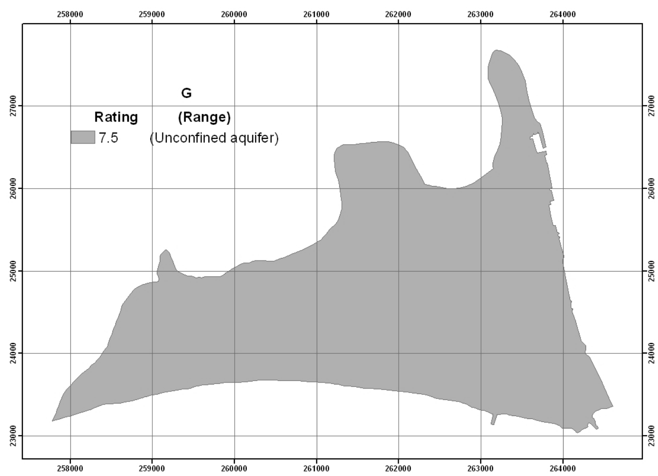

Fig. 3 Parameter G.

Parameter A: aquifer hydraulic conductivity The hydraulic conductivity ranges from values of 28 m day^{-1} to 76.3 m day^{-1} (as referred by Silva, 1984). From the known values we interpolated the values for the aquifer area using a kriging method; near the coastal line and near the alluvial areas adjacent to the Carrasqueira and Guadiana rivers smaller values were assigned. This conductivity values were used as input data for a groundwater flow and transport model developed for this aquifer by Diamantino *et al.* (2003). After calibration the initial hydraulic conductivity distribution was slightly rearranged and those calibrated values were then used for the GALDIT index computation (Fig. 4).

Parameter L: height of groundwater level above sea level The values adopted for this parameter were provided by the groundwater model calibration for the study area in steady state regime (*cf.* Diamantino *et al.*, 2003; Lobo-Ferreira *et al.,* 2003); this we considered as the first scenario of height of groundwater level above sea level (Fig. 5). Two additional scenarios were considered, one corresponding to a potential rise in sea level of 0.25 m (Fig. 6) and another of 0.5 m (Fig. 7). These scenarios may be considered as equivalent to scenarios of decreases of regional groundwater level, due to overexploitation, of the same order of magnitude.

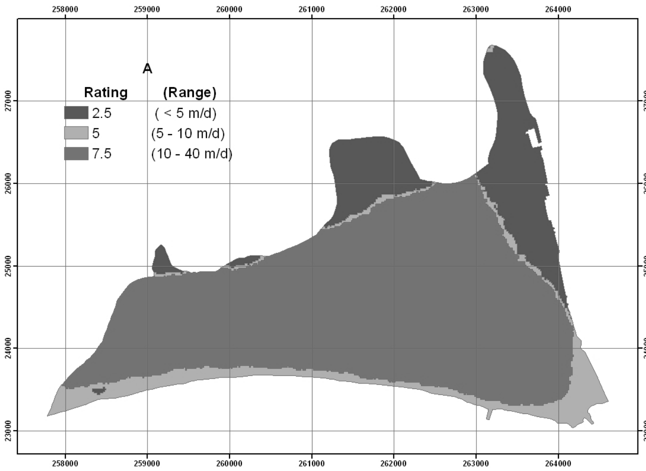

Fig. 4 Parameter A.

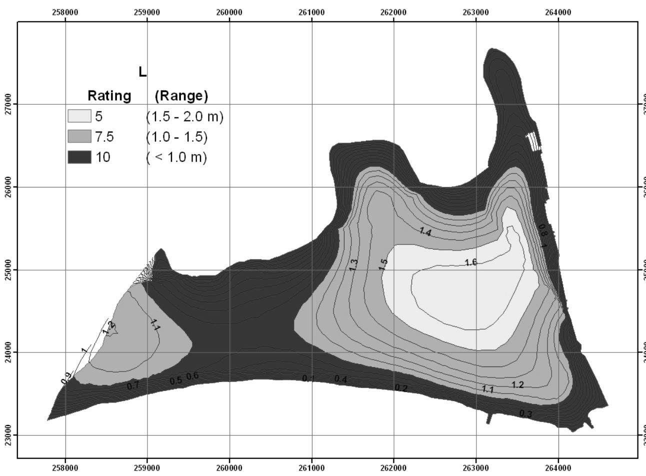

Fig. 5 Parameter L for the first scenario (today's sea level).

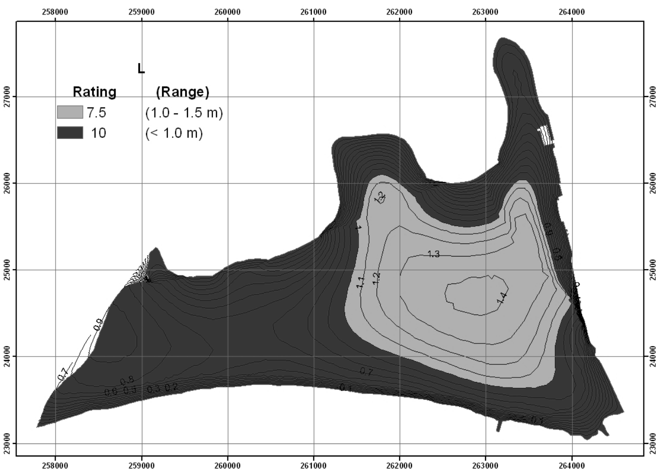

Fig. 6 Parameter L for the second scenario (sea level rises 0.25 m).

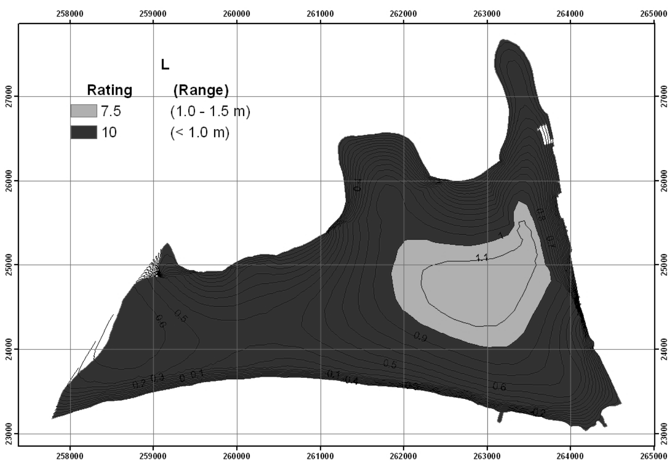

Fig. 7 Parameter L for the third scenario (sea level rises 0.5 m).

Parameter D: distance from the shore This parameter was computed calculating three perpendicular distances (i.e. 500, 750 and 1000 m) from the coastal line in the southern part of the aquifer, and from the rivers banks of Carrasqueira, in the northern part, and Guadiana, in the southeast part of the aquifer. As mentioned, the surface waters in these rivers are brackish, so seawater intrusion vulnerability in these areas has the same practical negative effects as those of the coastal zone. The distribution of GALDIT parameter D is presented in Fig. 8.

Parameter I: impact of existing status of seawater intrusion To evaluate this parameter the ratio of Cl^- / $HCO_3^{-(1)}$ (the formula used in this paper is a simplification of that in Chachadi & Lobo-Ferreira (2007). In this paper we considered as nil the usually smaller contribution of CO_3^{2-} in the recommended ratio of Cl^- / [HCO_3^{-1} + CO_3^{2-}], as CO_3^{2-} values were not known for the study area) was determined for those wells that have available the concentrations of those two anions. The distribution of GALDIT parameter is presented in Fig 9 and the ratios used for mapping this distribution are presented in Table 1.

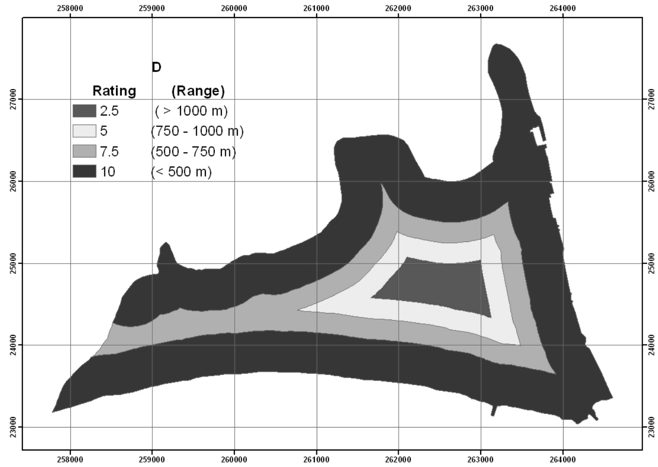

Fig. 8 Parameter D.

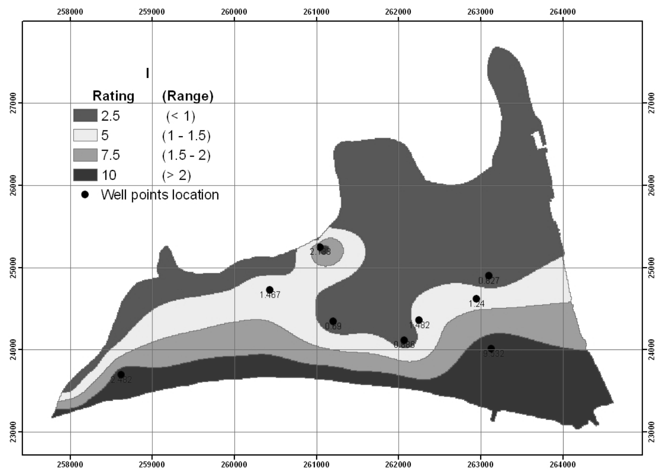

Fig. 9 Parameter.

Table 1 Ratio Cl^-/ HCO_3^- used for Galdit parameter I.

Well identification number	Coordinates		RATIO
	M	P	Cl^- / HCO_3
600090017 – G17	258619	23698	2.48
600071005 – GG5	260429	24731	1.47
600071006 – GG6	261047	25252	2.13
600090054 – AC1	261200	24350	0.69
600090043 – JK3	262070	24120	0.89
600090057	262250	24360	1.48
600090041	262950	24620	1.24
600090056	263100	24900	0.83
600090049 – G49	263128	24014	19.53

Parameter T: thickness of aquifer The aquifer system of Monte Gordo is 12 m thick, so a rating value of 10 was assigned to this parameter (Fig. 10).

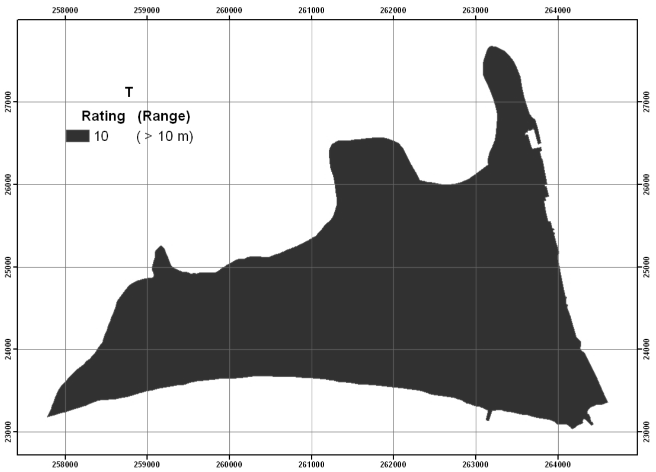

Fig. 10 Parameter T.

CONCLUSIONS

The new method of aquifer vulnerability mapping due to sea water intrusion i.e. the GALDIT method developed by Chachadi & Lobo-Ferreira (2001) 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 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 the equations presented in Chachadi & Lobo-Ferreira (2007) 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 required 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 a GIS platform by defining the areas having such hydrogeological situation as a separate layer.

The three scenarios applied regarding the parameter L, *Height of Groundwater Level above Sea Level*, and observing Figs 11, 12 and 13 show how important it is to assess in advance the impact of sea water level rise due to climate changes. These figures are also important to observe the negative effects of overexploitation of aquifers, which affects regional groundwater level, causing coastal zone salt water intrusion.

The reader is invited to complement this reasoning, on the effects of sea water rise in aquifers, by comparing the values presented before for Monte Gordo aquifer with those computed for the Bardez aquifer in Goa, India, presented in Part 2 of this paper (also included in the Proceedings of this 4th InterCeltic Colloquium), i.e. in Chachadi & Lobo-Ferreira (2005).

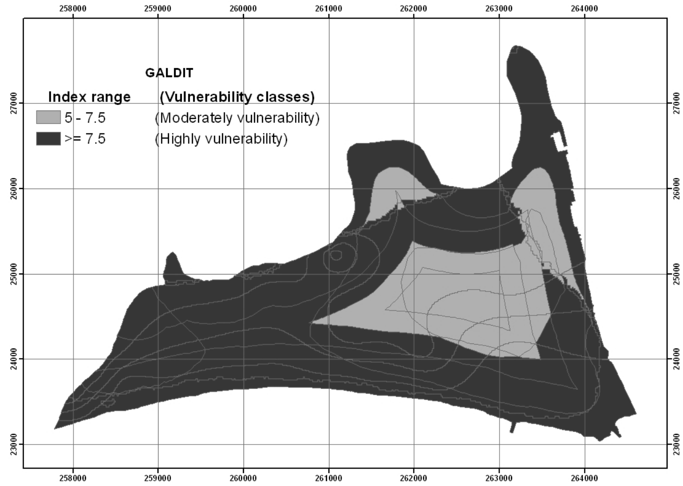

Fig. 11 Computed GALDIT index for the first scenario (today's sea level).

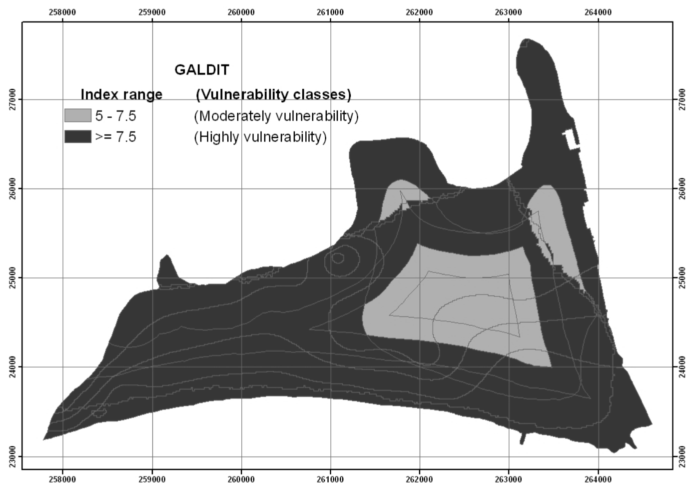

Fig. 12 Computed GALDIT index for the second scenario (sea level rises 0.25 m).

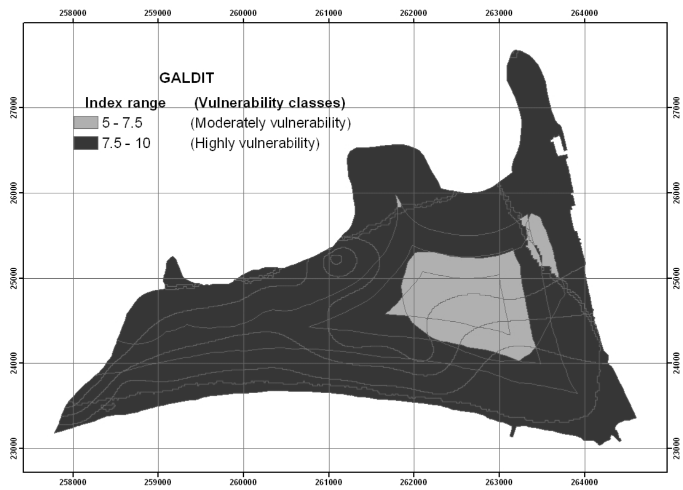

Fig. 13 Computed GALDIT index for the third scenario (sea level rises 0.5 m).

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