Assessing aquifer vulnerability to seawater intrusion using GALDIT method: Part 1 - Application to the Portuguese Aquifer of Monte Gordo

JOÃO PAULO LOBO FERREIRA[1], A. G. CHACHADI[2], CATARINA DIAMANTINO[3], M. J. HENRIQUES[4]

[1,3,,4] Laboratório Nacional de Engenharia Civil (LNEC), Hydraulics and Environment Department (DHA),
Groundwater Division (NAS), Av. do Brasil, 101, 1700-066 Lisboa, Portugal
Tel: +351 21 844 3609, lferreira@lnec.pt[1] Fax: +351 21 844 3016
[2] Lecturer at Goa University, Dept. of Earth Science, Goa University, Goa – 403 206, India,
chachadi1@rediffmail.com

Abstract This paper is divided in 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 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 application of the method is exemplified in the paper for the assessment of aquifer vulnerability to sea-water 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 other to determine the relative importance of each factor.

Part 2 of the paper is available in the Proceedings of this 4th Interceltic Colloquium as CHACHADI and LOBO-FERREIRA (2005). In the second part of the paper the method for assessing GALDIT index parameters is fully explained and an application to a costal aquifer located in Goa, not only for today's conditions but also considering a 0.5 m sea level rise are presented.

Key Words Aquifer vulnerability, groundwater protection, modelling, sea water intrusion.

PROBLEM DEFINITION

Continued human interference with the coastal hydrologic system has led to pollution of coastal groundwater aquifers by salt water. Incidence of groundwater pollution due to salt-water intrusion has increased manifold in the last two decades.

Assessing aquifer vulnerability to seawater intrusion using GALDIT method: Part 1 - Application to the Portuguese Aquifer of Monte Gordo

JOÃO PAULO LOBO FERREIRA[1], A. G. CHACHADI[2], CATARINA DIAMANTINO[3], M. J. HENRIQUES[4]

[1,3,,4] Laboratório Nacional de Engenharia Civil (LNEC), Hydraulics and Environment Department (DHA),
Groundwater Division (NAS), Av. do Brasil, 101, 1700-066 Lisboa, Portugal
Tel: +351 21 844 3609, lferreira@lnec.pt[1] Fax: +351 21 844 3016
[2] Lecturer at Goa University, Dept. of Earth Science, Goa University, Goa – 403 206, India,
chachadi1@rediffmail.com

Abstract This paper is divided in 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 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 application of the method is exemplified in the paper for the assessment of aquifer vulnerability to sea-water 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 other to determine the relative importance of each factor.
Part 2 of the paper is available in the Proceedings of this 4th Interceltic Colloquium as CHACHADI and LOBO-FERREIRA (2005). In the second part of the paper the method for assessing GALDIT index parameters is fully explained and an application to a costal aquifer located in Goa, not only for today's conditions but also considering a 0.5 m sea level rise are presented.

Key Words Aquifer vulnerability, groundwater protection, modelling, sea water intrusion.

PROBLEM DEFINITION

Continued human interference with the coastal hydrologic system has led to pollution of coastal groundwater aquifers by salt water. 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 in the fresh water aquifers. The smaller the drop in groundwater levels, the lesser the sea water intrusion in 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 dependent largely on 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 sea water 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 and LOBO-FERREIRA (2001) and presented in CHACHADI and LOBO-FERREIRA (2005).

DEFINITION OF GROUNDWATER VULNERABILITY TO SEA WATER INTRUSION

Following the basic concepts presented in LOBO-FERREIRA and 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 sea water intrusion to 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 hydrogeologic setting is the physical characteristics that affect the seawater intrusion potential. The most important mapable factors that control the seawater intrusion are found to be:

- Groundwater Occurrence (aquifer type; unconfined, confined and leaky confined).
- Aquifer Hydraulic Conductivity.
- Height of Groundwater Level above Sea Level.
- Distance from the Shore (distance inland perpendicular from shoreline).
- Impact of existing status of seawater intrusion in the area.
- Thickness 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: Identification of all the indicators influencing the seawater intrusion episode. This task was achieved through extensive discussions and consultations with the experts, academicians 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, 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 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 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, corresponds to more vulnerable aquifers to seawater intrusion.

Due to the limited number of pages available for this publication it is not possible to describe 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 and LOBO-FERREIRA (2005), 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 in 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 and LOBO-FERREIRA (2005).

GALDIT APLICATION 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 as 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 sands dune reaching more than 10 meters 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, overlaying an impermeable substratum constituted by silts and clays, of unknown thickness, considered as old alluviums; underlying this level the coloured Pliocene sandstone appear. The saturated zone corresponds to a sand level with a thickness estimated to be 12 meters; at the surface a sand dune system occurs, which thickness depends on the topography, exceeding, sometimes, 10 meters. According to several geologic profiles published by SILVA (1984), the impermeable substratum is practically horizontal with a slightly inclination towards 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. Fig. 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, having about 12 meters of saturated thickness. The covering sand dunes do not exceed 10 meters in thickness. Fig. 2 shows an N-S conceptual cross-section of the aquifer where one can observe the above mentioned formations and the existence of two saltwater-freshwater interfaces, one along the Carrasqueira River and the other along the coastal zone. On the side of the ocean the salt water content is about 36 g/L, 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.

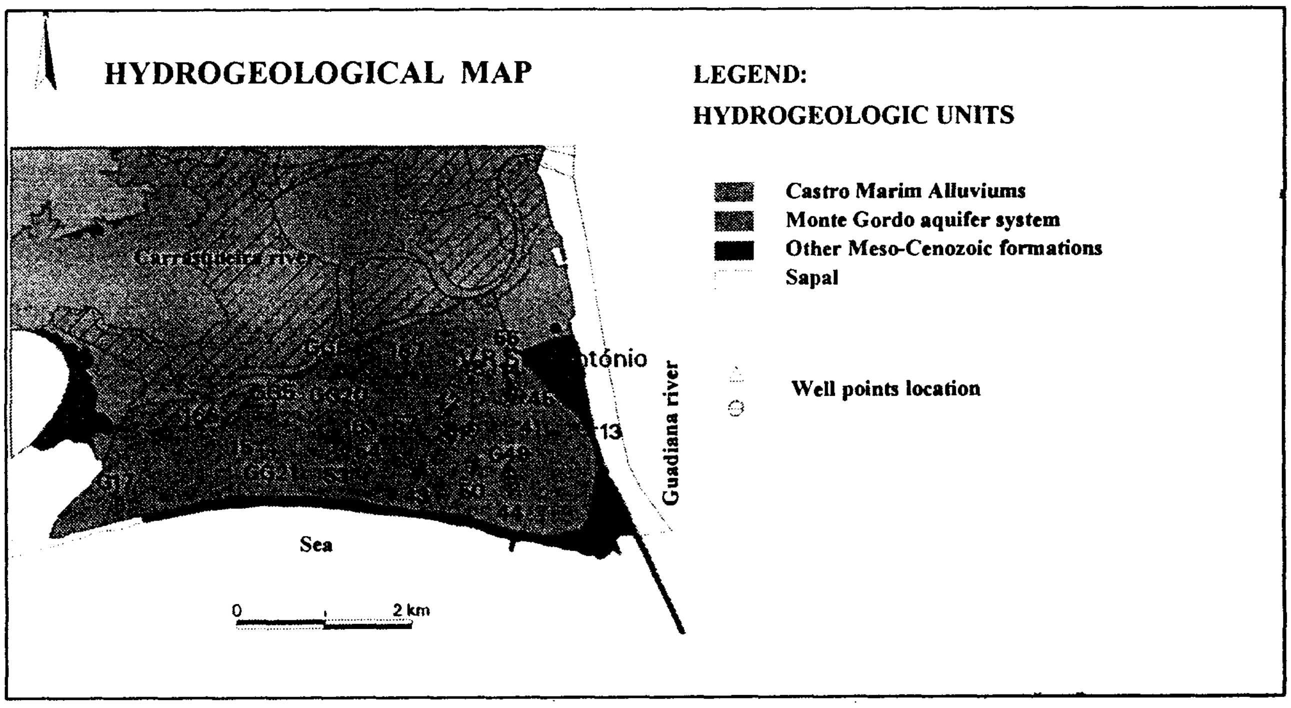

Fig. 1 – Hydrogeological map of the aquifer system of Monte Gordo

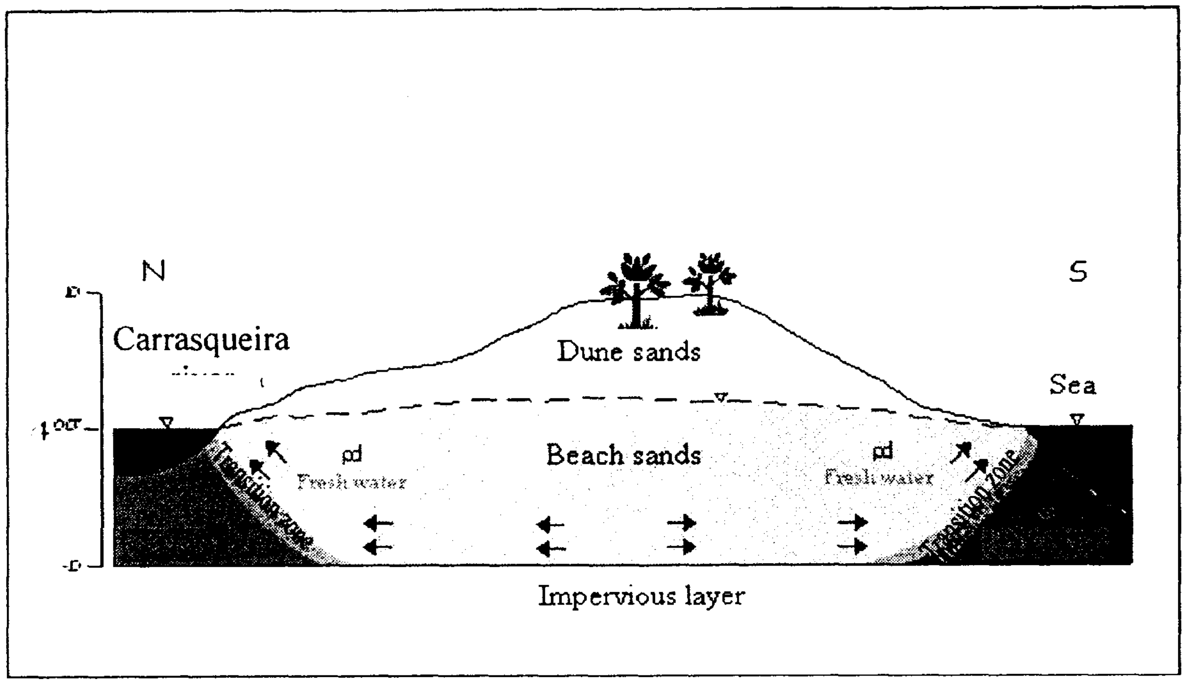

Fig. 2 N-S conceptual cross-section of the aquifer system of Monte Gordo

For application to the Monte Gordo aquifer system the six GALDIT parameters were evaluated. Those parameters have been assessed for natural conditions (i.e. no significant pumping rates for this case-study).

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).

Parameter A: Aquifer Hydraulic Conductivity

The hydraulic conductivity ranges from values of 28 m/day to 76,3 m/day (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.

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 it was 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⁾ was determined for those wells that have available the concentrations of those two anions. The distribution of GALDIT parameter It is presented in Fig 9 and the ratios used for mapping this distribution are presented in Table 1.

---

(1) The formula used in this paper is a simplification of the one presented in CHACHADI and LOBO-FERREIRA (2005). 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.

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).

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

Well identification number	Coordinates		RATIO Cl^- / $HCO3^-$
	M	P	
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

NB: M: Portuguese reference meridian coordinates; P = Portuguese reference parallel coordinates

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 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 and LOBO-FERREIRA (2005) 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.

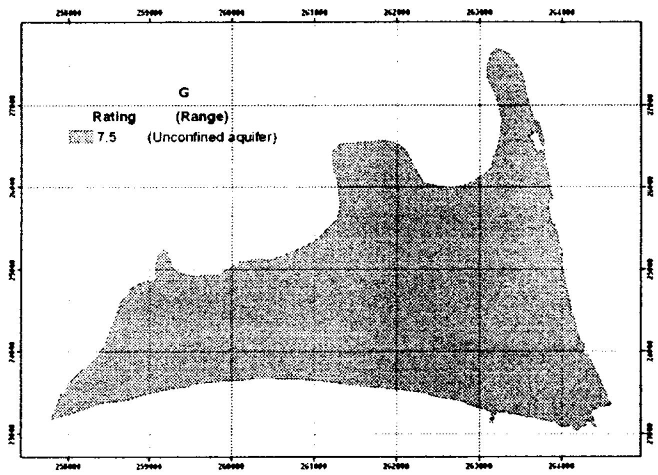

Fig. 3 – Parameter G

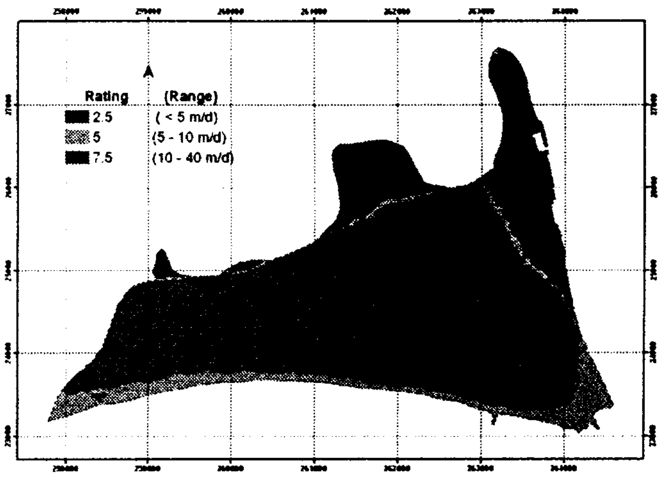

Fig. 4 – Parameter A

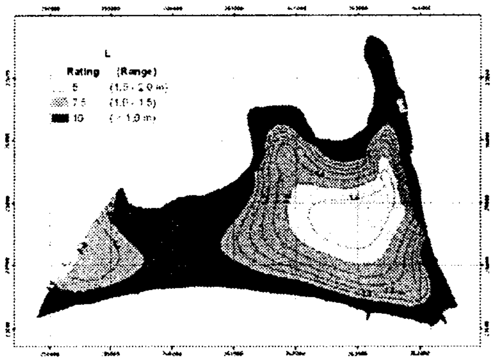

Fig. 5 – Parameter L for the first scenario (today's sea level)

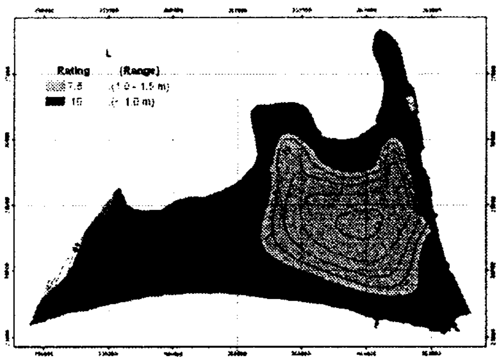

Fig. 6 – Parameter L for the second scenario (sea level rises 0.25 m)

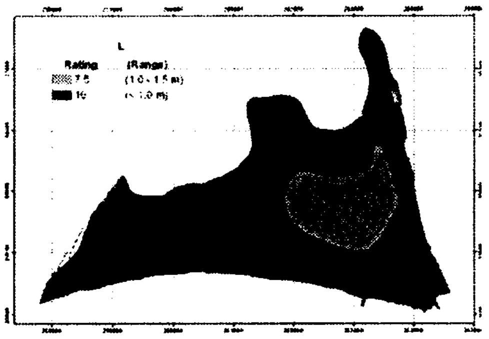

Fig. 7 – Parameter L for the third scenario (sea level rises 0.5 m)

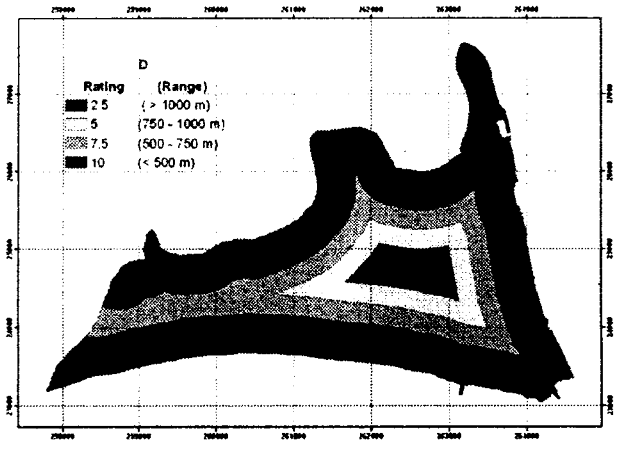

Fig. 8 – Parameter D

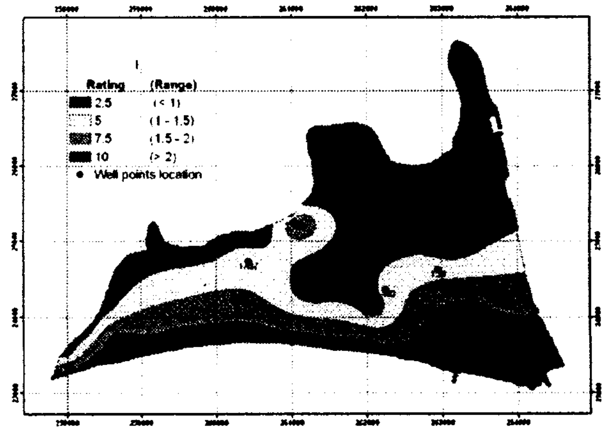

Fig. 9 – Parameter I

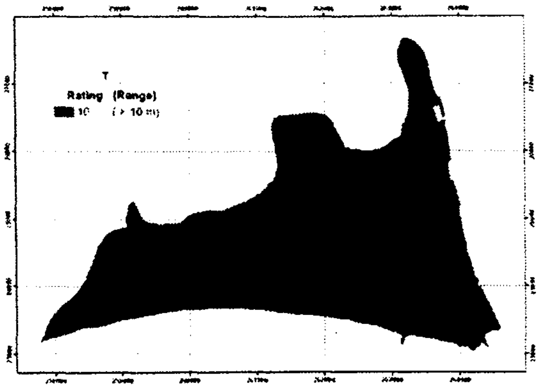

Fig. 10 – Parameter T

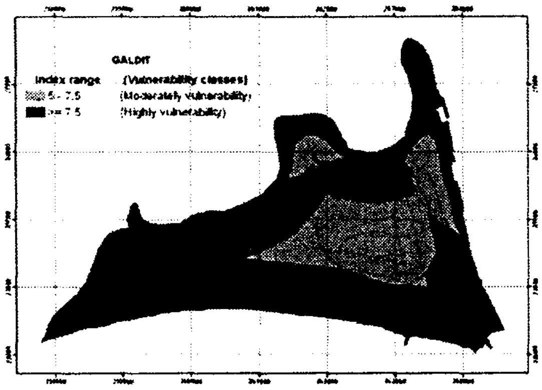

Fig. 11 – Computed GALDIT index for the first scenario (today's sea level)

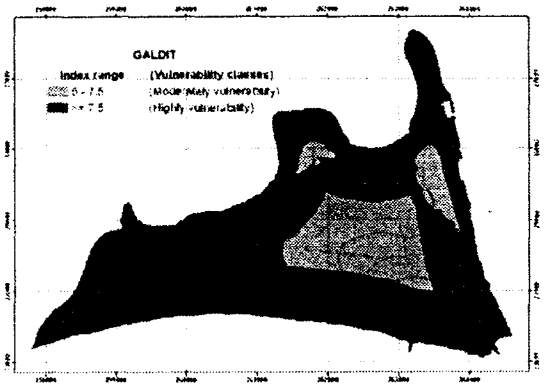

Fig. 12 – Computed GALDIT index for the second scenario (sea level rises 0.25 m)

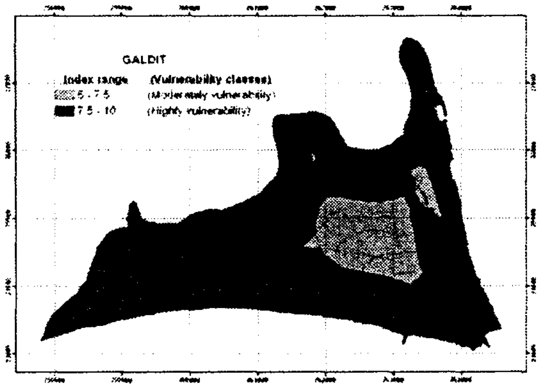

Fig. 13 – Computed GALDIT index for the third scenario (sea level rises 0.5 m)

The three scenarios application 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 on due time the impact of sea water level rise do to climate changes. These figures are also important to observe the negative effects of overexploitation of aquifers, which affects regional groundwater level, causing in 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 and LOBO-FERREIRA (2005).

ACKNOWLEDGEMENTS

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

REFERENCES

Chachadi A.G. & Lobo-Ferreira, J.P (2001), Sea water intrusion vulnerability mapping of aquifers using GALDIT method. Proc. Workshop on modelling in hydrogeology, Anna University, Chennai, pp.143-156, and in COASTIN A Coastal Policy Research Newsletter, Number 4, March 2001. New Delhi, TERI, pp. 7-9, (cf. *http://www.teriin.org/teri-wr/coastin/newslett/coastin4.pdf*).

Chachadi A.G & Lobo-Ferreira, J.P (2005), Assessing aquifer vulnerability to sea-water intrusion using GALDIT method: Part 2 – GALDIT Indicator Descriptions. IAHS and LNEC, Proceedings of the 4th The Fourth Inter Celtic Colloquium on Hydrology and Management of Water Resources, held at Universidade do Minho, Guimarães, Portugal, July 11- 13, 2005.

Diamantino, C., Oliveira, M.M., Lobo-Ferreira, J.P. & Moinante, M.J. (2003), Estudo das Condições Ambientais no Estuário do Rio Guadiana e Zonas Adjacentes Componente Águas Subterrâneas. Relatório da 3.ª Fase, Proposta de Medidas de Gestão Ambiental. Relatório 179/03 - NAS, LNEC, Lisboa, Julho de 2003.

INAG (1997), Definição, Caracterização e Cartografia dos Sistemas Aquíferos de Portugal Continental. Lisboa, Instituto da Água, Direcção dos Serviços de Recursos Hídricos, Divisão de Recursos Subterrâneos.

Lobo-Ferreira, J.P., Diamantino, C., Leitão, T.E., Oliveira, M.M., Moinante, M.J., Artuso, E. and Zakharova, T. (2003), Projecto FCT Valorização e Protecção da Zona Costeira Portuguesa: Avaliação e Estudo da Vulnerabilidade de Sistemas Aquíferos Costeiros (Componente 11). Relatório 265/03-NAS, LNEC, Lisboa, Julho de 2003, 189 pp.

Lobo-Ferreira, J.P.& 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.

Silva, M.O. (1984), Hidrogeologia do Algarve Oriental. Lisboa, Faculdade de Ciências da Universidade de Lisboa, Departamento de Geologia, Tese de Doutoramento.