Aquifer development planning to supply a seaside resort: a case study in Goa, India

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Abstract Using the hydrogeological and socio-economic data derived from a European Commission research project on the measurement, monitoring and sustainability of the coastal environment, two optimization models have been applied to satisfy the future water resources needs of the coastal zone of Bardez in Goa, India. The number of tourists visiting Goa since the 1970s has risen considerably, and roughly a third of them go to Bardez taluka, prompting growth in the tourist-related infrastructure in the region. The optimization models are non-linear mixed integer models that have been solved using GAMS/DICOPT++ commercial software. Optimization models were used, firstly, to indicate the most suitable zones for building seaside resorts and wells to supply the tourist industry with an adequate amount of water, and secondly, to indicate the best location for wells to adequately supply pre-existing hotels. The models presented will help to define the optimal locations for the wells and the hydraulic infrastructures needed to satisfy demand at minimum cost, taking into account environmental constraints such as the risk of saline intrusion.

Résumé A l'aide de données hydrogéologiques et socio-économiques, dérivées d'un projet de recherche de la Commission Européenne sur l'étude, la surveillance et la durabilité de l'environnement côtier, deux modèles d'optimisation ont été appliqués en vue de satisfaire les besoins futurs en ressources en eau de la zone côtière de Bardez au Goa en Inde. Le nombre de touristes qui visitent le Goa depuis les années 70 a considérablement augmenté et environ un tiers d'entre eux se rend à Bardez taluka, ce qui encourage la croissance des infrastructures liées au tourisme dans la région. Les modèles d'optimisation sont des modèles non linéaires mixtes en nombres entiers qui ont été résolus en utilisant le logiciel commercial GAMS/DICOPT++. Les modèles d'optimisation ont été utilisés pour indiquer premièrement les zones les plus appropriées pour construire des stations balnéaires et des puits pour approvisionner en quantité d'eau suffisante l'industrie touristique, et deuxièmement pour indiquer la meilleure localisation de puits pour l'alimentation des hôtels préexistants. Les modèles présentés aideront à définir les localisations optimales des puits et des infrastructures hydrauliques nécessaires à la satisfaction de la demande à un coût minimum, tout en prenant en compte les contraintes environnementales, tel que le risque d'intrusion saline.

Resumen Se han aplicado dos modelos de optimización en base a datos socio-económicos e hidrogeológicos derivados de un proyecto de investigación de la Comisión Europea sobre medición, monitoreo y sostenibilidad del ambiente costero para satisfacer las necesidades futuras de recursos hídricos de la zona costera de Bardez en Goa, India. El número de turistas que visita Goa desde la década de 1970´s ha subido considerablemente y cerca de un tercio de ellos van a Bardez taluka impulsando el crecimiento en la infraestructura turística de la región. Los modelos de optimización son modelos de números enteros mixtos no-lineales que se han resuelto usando el programa comercial GAMS/DICOPT++. Los modelos de optimización se usaron, primero para indicar las zonas más adecuadas para la construcción de centros de diversión en las márgenes del océano y pozos para abastecer la industria turística con una adecuada cantidad de agua, y

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segundo, para indicar la mejor localización de pozos para el abastecimiento de hoteles pre-existentes. Los modelos que se presentan ayudarán a definir las localizaciones óptimas para los pozos y las infraestructuras hidráulicas necesarias para satisfacer la demanda al mínimo costo, tomando en consideración restricciones ambientales tal como el riesgo de intrusión salina.

Keywords Groundwater management · Optimization · Environment indicators · Groundwater protection · Salinization

Introduction

A research project, supported by the European Commission's Programme for International Cooperation with Developing Countries (INCO-DEV), entitled "Measuring, Monitoring and Managing Sustainability: The Coastal Dimension" has been completed (TERI 2003). Based on the hydrogeological and socio-economic data provided by the project, Lobo-Ferreira et al. (2003) presented an application of optimization models to satisfy the future water resource needs of tourist-related infrastructures (tourist resorts) along the coastal zone of Bardez in Goa, India.

There has been a marked increase in the number of tourists visiting the state of Goa since the 1970s, and roughly a third of them go to Bardez taluka (Fig. 1). Goa, which has an area of 3,702 km^2, has a tropical climate with three seasons: a wet monsoon period from June to September (providing precipitation of 2,500–4,300 mm during that period), a winter season from October to January, and a summer season from February to May. The population density of Goa is about 316/km^2 (census 1991).

The case study area is a coastal area of 120 km^2, situated in the north-western corner of Goa in the district of Bardez, and its population density is 717/km^2. The lithology consists of laterites and sands, which form unconfined aquifers, overlying Precambrian metamorphic and crystalline rocks (Fig. 2).

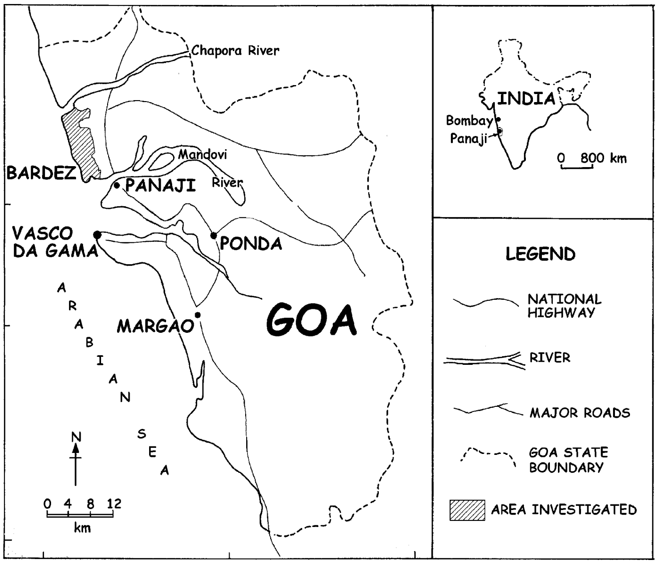

Fig. 1 Bardez case study area, located in the Indian state of Goa

Hydrogeological assessment of the unconfined Bardez aquifers has been carried out and is synthesized in Chachadi et al. (2001) and Nagel et al. (2001). The data enable mathematical groundwater-flow models to be applied, and also allows the assessment and mapping of groundwater vulnerability to pollution (Fig. 3), based on the DRASTIC index method (Aller et al. 1987). The DRASTIC index measures the vulnerability of the aquifer based on its intrinsic characteristics. These are static and beyond human control. The index corresponds to the weighted average of seven values, corresponding to seven hydrological parameters: depth to water table, net recharge, aquifer material, soil type, topography, impact of the unsaturated zone and hydraulic conductivity. High values of the index correspond to high vulnerability. The minimum value is 23 and the maximum is 226.

During the development of this research project, a new methodology to delineate wellhead protection zones in the Bardez region's unconfined aquifers was developed (Lobo-Ferreira and Krijgsman 2001; Krijgsman and Lobo-Ferreira 2001). Indicators were developed, which take account of groundwater extraction and the risk of saltwater intrusion, i.e. safe extraction rates for coastal zone pumping wells (both the existing ones and those needed to meet future water needs).

The results of coastal fresh-water pollution studies indicate very clearly that there are non-polluted waters in

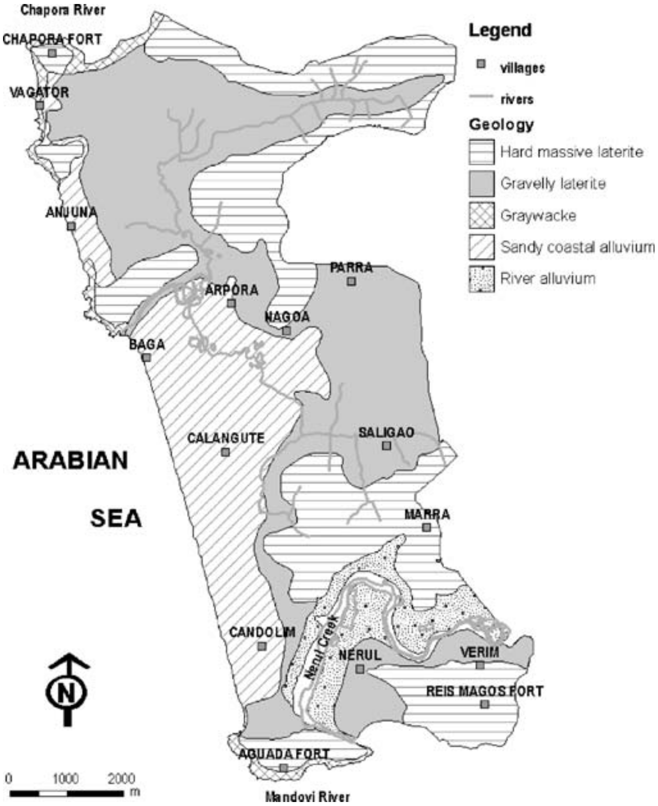

Fig. 2 Geology of Bardez case study area

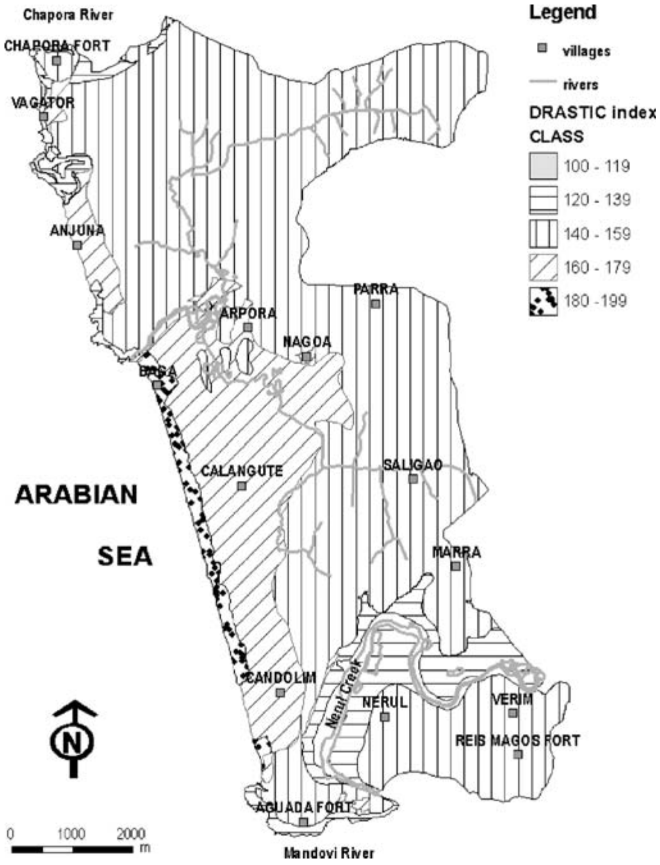

Fig. 3 DRASTIC index map of the Bardez study area. High index values correspond to high vulnerability

the study area of north Goa. The concentrations of dissolved oxygen (DO) and biochemical oxygen demand (BOD), the two most sensitive environmental parameters, and micronutrients such as nitrate-N and phosphate-P indicate that the waters are well circulated and clean.

Hydrogeological data

Hydrogeological data on the Bardez case-study area are available for the following parameters: hydraulic gradient i, saturated thickness of the aquifer *b*, hydraulic conductivity *K* and effective porosity *n*. Groundwater level data, which are essential for deriving i, are available for 57 wells, for all seasons. Saturated aquifer thickness data are available for 53 wells. Hydraulic conductivity data are available for six wells, ranging between 1.4 and 31 m/d. Effective porosity data are available for two types of aquifer: for lateritic aquifers, *n* varies between 0.20 and 0.30 (an average of 0.25 was considered for this work); for sandy aquifers, *n* varies between 0.15 and 0.35 (an average of 0.25 was considered).

Lobo-Ferreira and Krijgsman (2001) and Krijgsman and Lobo-Ferreira (2001) studied and mapped the distribution of the regional hydraulic gradient i for the wet season, the regional distribution of the saturated thickness of the aquifer *b* in the wet season, the extrapolated distribution of the regional hydraulic conductivities *K*, and the expected productivity of the aquifers.

Based on the hydrogeological data available, a response matrix was built with the coefficients of influence of the aquifer, using the Maddock (1972) approach (Lobo-Ferreira et al. 2002). The response matrix represents the drawdown values computed in all existing or potential pumping wells of the study area, caused by the extraction of 100 m^3/d of groundwater in just one well at a time. Figure 4 represents the location of each well in relation to the aquifer discretization used to run the MODFLOW groundwater flow numerical model.

Optimization of water needs for tourist resorts

Tourist development

The study area is rural, apart from the coastline, where many tourist resorts are located. Since the 1970s, there has been a remarkable increase in the number of tourists arriving in Goa. About one third of these tourists go to the coastal area described above, located in Bardez taluka. In 1991, the Indian rupee was devalued as one of the structural

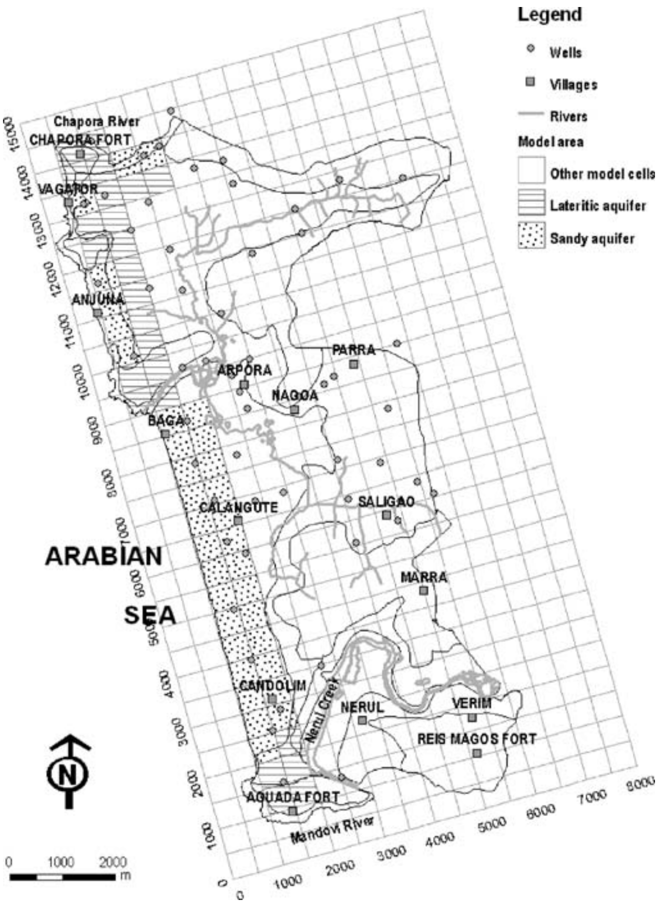

Fig. 4 The location of each well in relation to the aquifer discretization used to run the MODFLOW groundwater flow model. Cells relevant to groundwater use in tourist areas are at a distance of up to 1,000 m from the shore

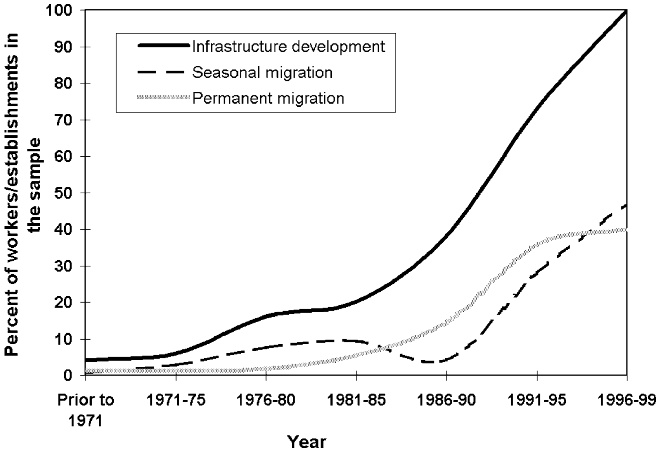

Fig. 5 Trends in tourist infrastructure development and migration in Calangute (TERI 2000)

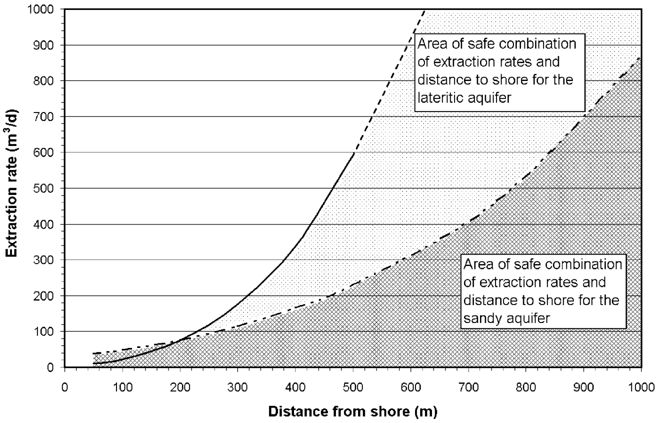

Fig. 7 Area of safe combination of extraction rates and distance to shore for the lateritic aquifer (hydraulic conductivity=4.3 m/d) and for the sandy aquifer (hydraulic conductivity=31.8 m/d)

reforms implemented by the Government. This devaluation led to a strong tourist demand for Goa. The increased tourism in Goa was also the result to socio-political unrest in other parts of India, especially in Kashmir, which caused a diversion of foreign tourists into Goa. In response to the growth of tourism, the number of tourist-related infrastructures also increased. Figure 5, taken from Noronha et al. (2001), shows the increasing trend in both the number of tourist infrastructures and the amount of population resettlement towards the coastal zone of Bardez, especially around the village of Calangute, one of the most popular tourist destinations in Goa.

Computation of indicators related to safe extraction of groundwater vs. the distance from the sea shore

The questions raised during the optimization procedure were: How is it possible to find the optimal locations for the supply wells, and what are the most important parameters that have to be considered? How important is the number of wells and their distance to the hotels, taking into account the cost of coastal zone land, service-pipes, and running expenses? What is the relation between the extraction rate of the wells and the risk of saltwater intrusion? How is it possible to minimize this risk?

The relation between safe extraction rates and the distance of pumping wells from the seashore has been researched. This is one of the most interesting achievements of this study, and takes into consideration the aim of avoiding saltwater intrusion in the pumping wells. Figure 6 plots the saltwater/fresh-water interface calculated using the Ghyben-Dupuit approximation (Bear and Verruijt 1987).

The curves of Fig. 7 show the values obtained when the extraction rates vary from 50 to 1,000 m^3/d. The results were obtained by subtracting the depth of saltwater/fresh-water interface with static discharges ($D_{s,f}$) from the summation of the drawdown in the well during pumping (D_d) and the upcoming of saltwater into the fresh-water body, due to the pumping (U_c). If the result of the subtraction is greater than the thickness of the

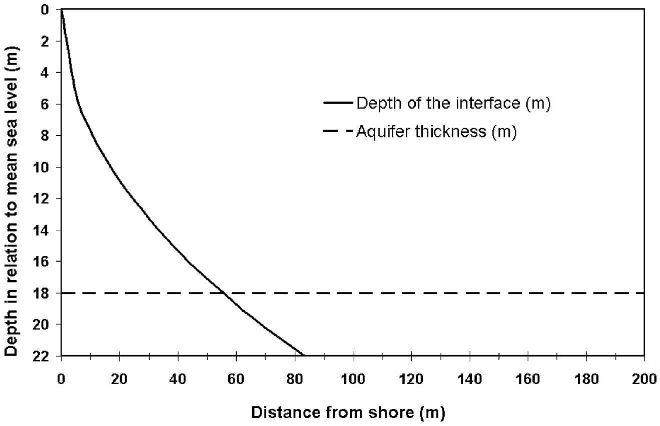

Fig. 6 Computational example of the fresh-water/saltwater interface using the Ghyben-Dupuit approximation for the Bardez coastal zone aquifers (infiltration rate=3.4 mm/d)

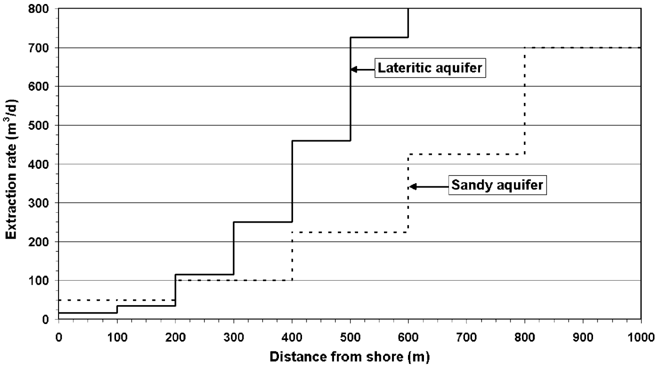

Fig. 8 Step function relations between the maximum extraction rates and the distance of the well from the shoreline, in order to prevent the risk of saltwater intrusion into the well, as a function of the aquifer medium

Table 1 Optimal solution for two total flow-rate demand (*QT*) scenarios: case study 1

QT=2,500 m^3/d			QT=4,500 m^3/d		
Cells	Q (m^3/d)	R (m)	Cells	Q (m^3/d)	R (m)
$\mathrm{Cel}_{1750,8750}$	225	1.8	$\mathrm{Cel}_{1250,13250}$	301	13.3
$\mathrm{Cel}_{1750,7250}$	225	4.6	$\mathrm{Cel}_{1250,12250}$	178	14.0
$\mathrm{Cel}_{1750,6250}$	700	9.9	$\mathrm{Cel}_{1250,11250}$	243	15.0
$\mathrm{Cel}_{1750,5750}$	650	9.6	$\mathrm{Cel}_{1750,8750}$	225	1.9
$\mathrm{Cel}_{1750,2750}$	700	6.9	$\mathrm{Cel}_{1750,7250}$	225	4.8
			$\mathrm{Cel}_{1750,6250}$	700	10.3
			$\mathrm{Cel}_{1750,5750}$	700	10.5
			$\mathrm{Cel}_{1250,4750}$	225	3.2
			$\mathrm{Cel}_{1250,3750}$	225	2.9
			$\mathrm{Cel}_{1750,2750}$	700	7.9
			$\mathrm{Cel}_{1250,2250}$	400	4.6
			$\mathrm{Cel}_{1250,1250}$	378	15.0
Cost=137×10^3 Euros			Cost=354×10^3 Euros		

(Cel $_{x,y}$ represents the well location-subscripts correspond to coordinates in Fig. 4, *R* drawdown in the cells after pumping *Q*)

saturated aquifer (*b*; i.e. in this case 18 m), there will be saltwater intrusion into the pumping well.

To make the relations shown in Fig. 7 easier to handle, the two functions, i.e. curves, were transformed into step functions (Fig. 8), with distance steps of 100 m for the lateritic aquifer region and 200 m for the sandy aquifer region. In Fig. 8, it is very easy to see possible combinations of maximum extraction rate and distances from shore.

Optimization models and case studies

Case study 1

The first optimization model will make it possible to find the best location of the wells to provide a given flow rate (in the cells in Fig. 4). Its application will indicate the most suitable zones for building tourist hotels, from the standpoint of providing their water supply at minimum cost.

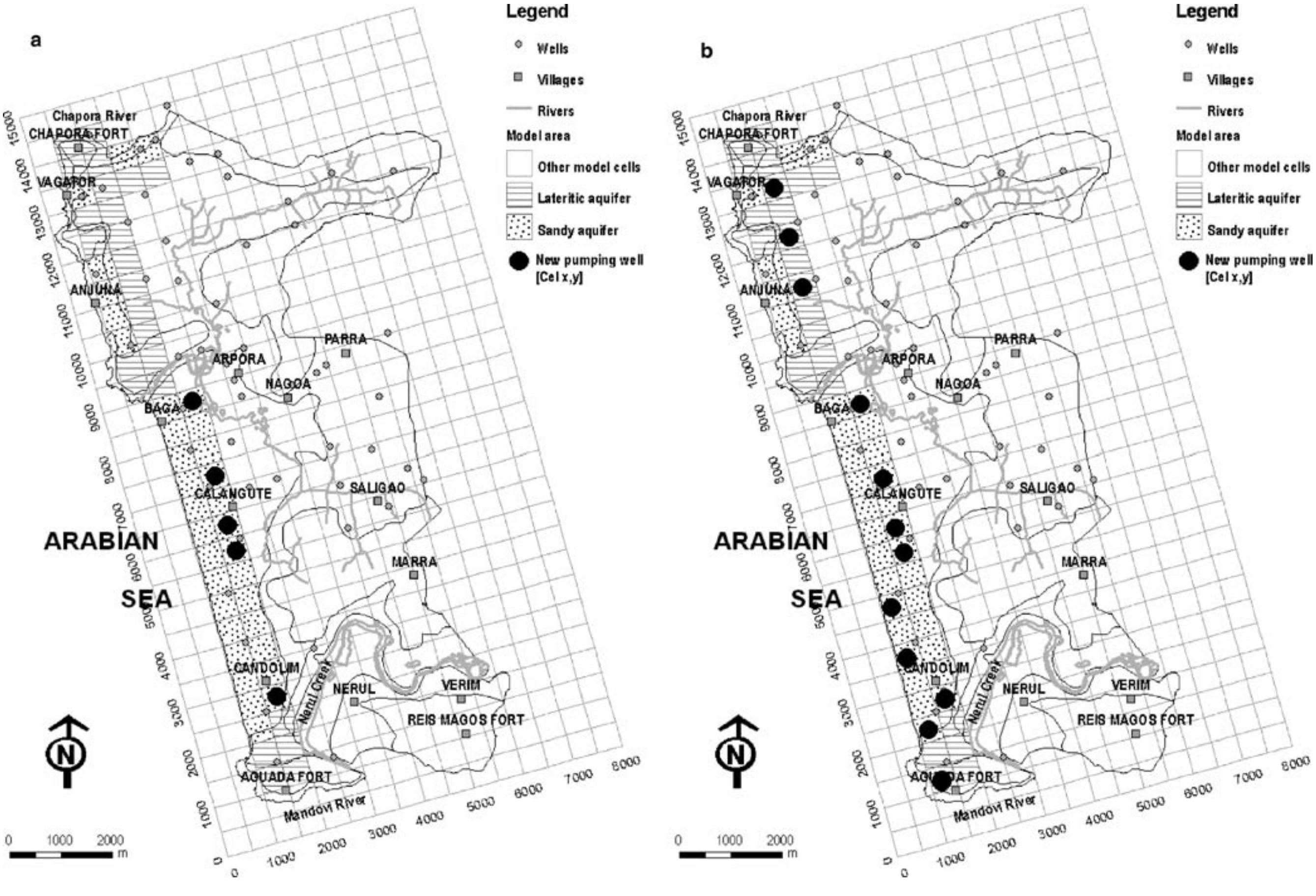

Fig. 9 **a** Example of an optimal solution for case study 1, where QT=2,500 m^3/d; cost=139,000 Euros; **b** example of an optimal solution for case study 1, where QT=4,500 m^3/d; cost=354,000 Euros

Table 2 Optimal solution for total demand (QT)=1000 m^3/d-Case study 2

$Loc_{2500,13500}$			$Loc_{1100,6000}$			$Loc_{1100,1500}$		
Cells	Q (m^3/d)	R (m)	Cells	Q (m^3/d)	R (m)	Cells	Q (m^3/d)	R (m)
$Cel_{1250,\ 13250}$	343	15	$Cel_{1750,\ 6250}$	700	7.7	$Cel_{1750,\ 2750}$	664	6.5
$Cel_{1250,\ 12250}$	195	15	$Cel_{1750,\ 5750}$	300	6.0	$Cel_{1250,\ 1250}$	336	13.1
$Cel_{1250,\ 11250}$	238	15						
$Cel_{1250,\ 8750}$	224	1.4						
Cost=170×10^3 Euros			Cost=73×10^3 Euros			Cost=103×10^3 Euros		

Loc $_{x,y}$ represents the hotel location, Cel $_{x,y}$ represents the well location, subscripts correspond to coordinates in Fig. 4, R drawdown in the cells after pumping Q

The optimization model includes an objective function representing cost minimization relative to well installation, protection and operation (the data related to costs, which will be used in the optimization models, have been previously addressed by Lobo-Ferreira et al. 2002):

$$Min\sum_{i=1}^{N}(aQ_i+by_i)+\sum_{i=1}^{N}Cp_i(Dc_i)y_i+\sum_{i=1}^{N}cQ_i^dH_i^e+PV\left(\sum_{i=1}^{N}f_{em}Q_iH_i\right) \quad (1)$$

N: number of possible locations for the wells to be installed; Q_i: flow rate to be supplied by well i; a: unit cost of well installation; b: fixed cost of well installation; Cp_i: well protection cost (given as a function of the distance to the shoreline Dc_i); c, d, e: parameters of the pumps' cost function; H_i: pump head in well i; PV: present value of energy and maintenance costs; f_{em}: unit cost of energy and pump maintenance; y_i: binary variable that will take value 1 if a well is installed in location i, and take the value 0 otherwise.

The constraints will express all the physical, technological, socio-economic and regulatory aspects of the problem:

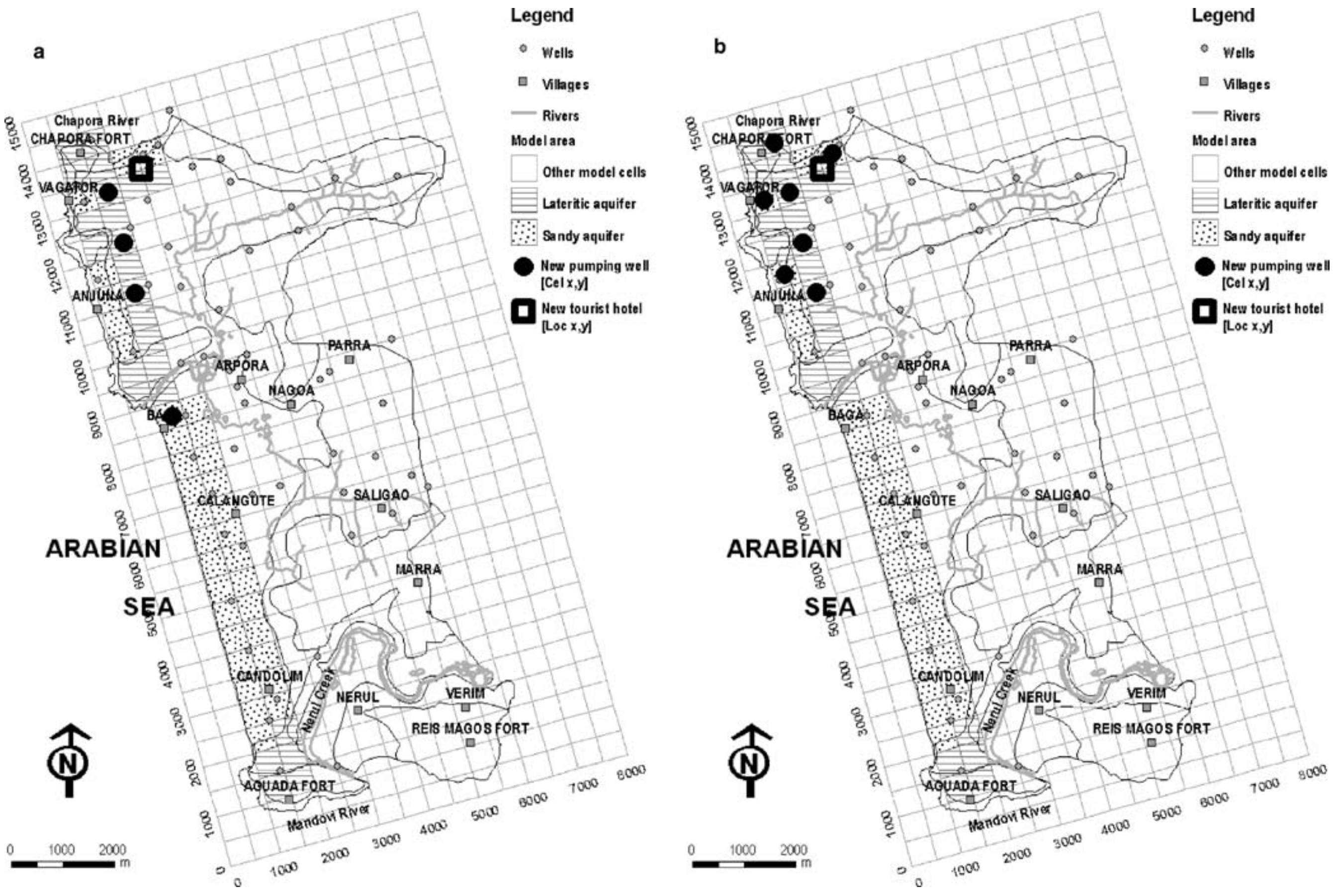

Fig. 10 Case study 2 ($Loc_{2500,13500}$) optimal solutions where: a) only drawdown constraints are limiting; b) the choice of cells located far from the hotel is prevented; c) saltwater intrusion constraints are ignored

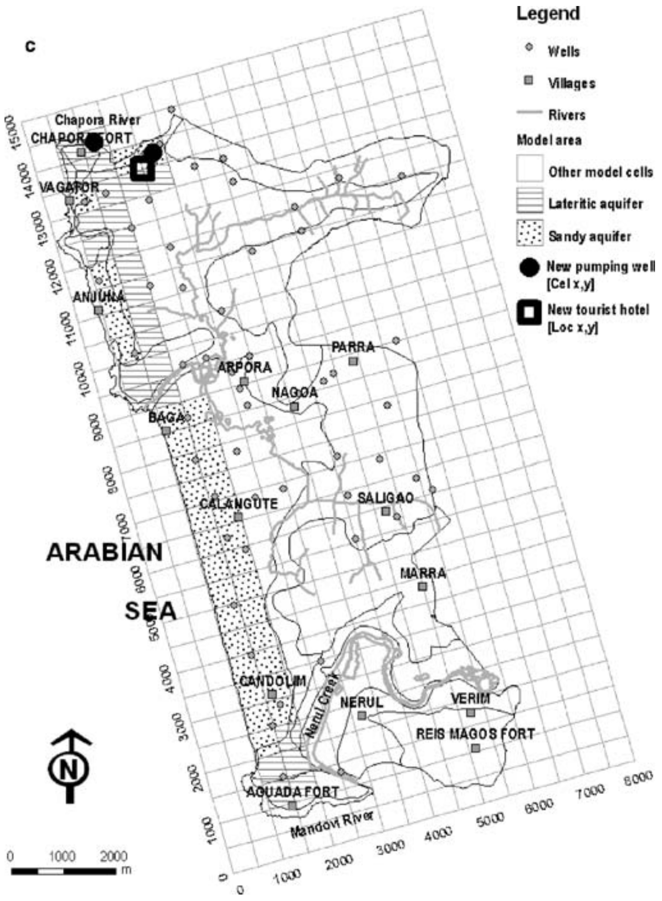

Fig. 10 (continued)

- Maximum extraction rate to be achieved for each well is constrained to a maximum value (Q_{imax}), in order to avoid saltwater intrusion. There will be extraction only in open wells. The values Q_{imax} are determined by the information given in Fig. 8:

$$Q_{\mathrm{i}} \leq y_{\mathrm{i}} Q_{\mathrm{imax}}, \forall \mathrm{i} \tag{2}$$

- Maximum drawdown in each cell is limited by a value (R_{imax}), depending on the physical characteristics of the aquifer

$$R_{\mathrm{i}} \leq R_{\mathrm{imax}}, \forall \mathrm{i} \tag{3}$$

$$\text{with } R_{\mathrm{i}} = \sum_{j=1}^{N} \alpha_{\mathrm{ij}} Q_{\mathrm{j}}, \forall \mathrm{i} \tag{4}$$

R_{i}: drawdown at cell i, resulting from the discharges from all the wells; α_{ij}: influence coefficient between well j and cell i (expresses the drawdown in cell i resulting from a unitary flow rate in well j, obtained through the use of MODFLOW)

- Total flow rate (QT) must satisfy the tourist demand

$$\sum_{\mathrm{i}=1}^{N} Q_{\mathrm{i}} = QT \tag{5}$$

Pump head is determined by

$$H_{\mathrm{i}} = Z_{\mathrm{i}} + R_{\mathrm{i}}, \forall \mathrm{i} \tag{6}$$

Z_{i}: distance between initial piezometric level and ground level at cell i.

The optimization model is a non-linear mixed integer model that has been solved using GAMS/DICOPT++ (Viswanathan and Grossmann 1990), in two operating scenarios: QT=2,500 m^3/d and QT=4,500 m^3/d.

The results obtained show that for the first scenario QT (see Table 1, where Cel $_{x,y}$ represents the wells location and subscripts correspond to coordinates in Fig. 4), the sandy cells furthest from the shore are those that were retained to provide the supply (Fig. 9a).

The results obtained for the second scenario QT (Table 1 and Fig. 9b), show that to satisfy a higher flow rate, some new cells have to be added. Some of these are located in the sandy aquifer; however, to obtain the total flow rate, some cells are located in the lateritic aquifer, a long way from the shore (Cel$_{1250,13250}$, Cel$_{1250,12250}$, Cel$_{1250,11250}$, Cel$_{1250,1250}$).

Case study 2

The second optimization model will find the best location for the wells that will provide a given amount of flow to supply a tourist hotel whose site is pre-defined. The optimization model includes an objective function representing cost minimization for well installation, protection and operation, and the pipes needed to convey the flow from the wells to the tourist hotel.

This objective function will be given by adding a term representing the costs of pipe installation and maintenance to the previous objective function:

$$Min \sum_{\mathrm{i}=1}^{N} (aQ_{\mathrm{i}} + by_{\mathrm{i}}) + \sum_{\mathrm{i}=1}^{N} Cp_{\mathrm{i}}(Dc_{\mathrm{i}}) y_{\mathrm{i}} + \sum_{\mathrm{i}=1}^{N} cQ_{\mathrm{i}}^{d} H_{\mathrm{i}}^{e}$$
$$+ PV\left(\sum_{\mathrm{i}=1}^{N} f_{\mathrm{em}} Q_{\mathrm{i}} H_{\mathrm{i}}\right) + \sum_{\mathrm{i}=1}^{N} Cc_{\mathrm{i}}(Q_{\mathrm{i}}, L_{\mathrm{i}}) \tag{7}$$

Cc_{i}: cost of the pipe that will transport the flow from well i, expressed as a function of the flow and the distance L_{i} between the well and the tourist hotel. The constraints are the same as before.

This model has been used for three possible tourist hotel sites (Table 2, where Loc $_{x,y}$ represents the hotel location and subscripts correspond to coordinates in Fig. 4): Loc$_{2500,13500}$, Loc$_{1100,\ 6000}$ and Loc$_{1100,\ 1500}$. The tourist hotel will represent a demand of 1,000 m^3/d (i.e. QT=1,000 m^3/d), with R_{imax}=15 m.

The results show that for the first scenario (Fig. 10a), the cells used to satisfy the demand are those that are simultaneously furthest from the shore and closest to the tourist hotel, until drawdown constraints are limiting (cells Cel$_{1250,13250}$, Cel$_{1250,12250}$, Cel$_{1250,11250}$). To complete the required total flow, the cell Cel$_{1250,8750}$ is also used. The reason for this choice (a cell far from the hotel) is that pumping in this cell will not have a big influence on the other cells whose drawdowns are close to the drawdown limitations.

If a new constraint is included to prevent the choice of a cell located so far away (i.e. below coordinates 1750, 11000), the results will be different (Fig. 10b). In this case, the results would be: $Cel_{1250,14250}$, $Cel_{2250,13750}$, $Cel_{750,13250}$, $Cel_{1250,13250}$, $Cel_{1250,12250}$, $Cel_{750,11750}$, $Cel_{1250,11250}$. It should be pointed out that, in this case, the cost would increase to 254×10^3 Euros. The reason for this increase is that cells where Q_{imax} is very small are being used ($Q_{1250,14250\mathrm{max}}$=25 m^3/d and $Q_{2250,13750\mathrm{max}}$= 50 m^3/d), because of the constraints relative to saltwater intrusion, given in Fig. 8. Even though, for the sake of costs minimization, it would be better to further exploit some wells, this would be impossible because of the constraints on flow rates (particularly in cells near the shoreline). For this reason, the economies of scale that would be made by concentrating pumping in a small number of wells are no longer possible.

If a hypothetical situation is evaluated, where saltwater intrusion constraints are ignored, the results would be (Fig. 10c): $Cel_{1250,14250}$ and $Cel_{2250,13750}$ ($Q_{1250,14250}$= 300 m^3/d and $Q_{2250,13750}$=700 m^3/d), and the cost would be 69×10^3 Euros.

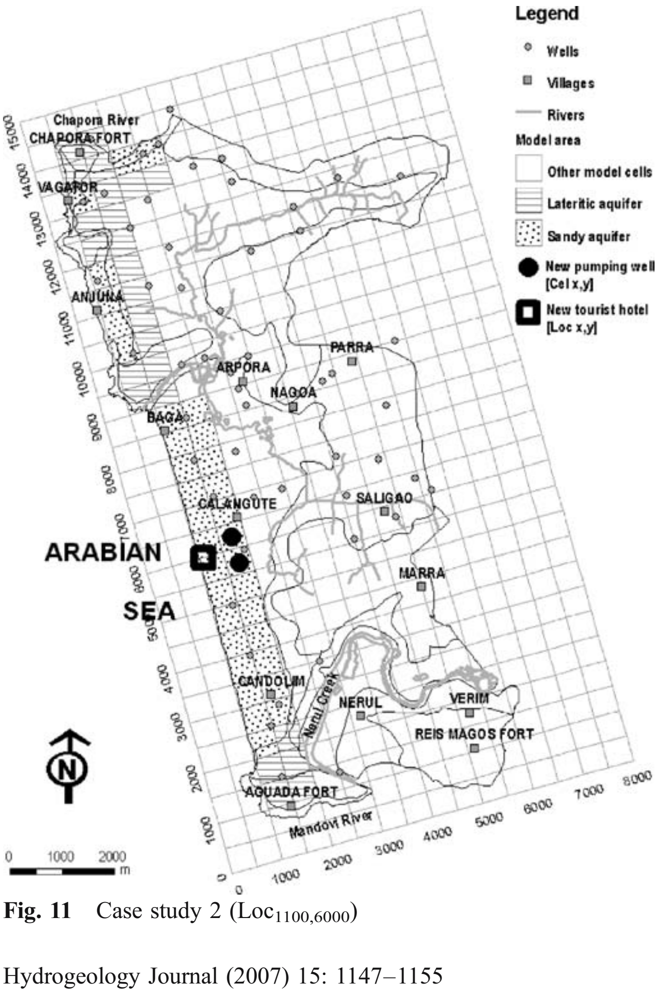

Fig. 11 Case study 2 ($Loc_{1100,6000}$)

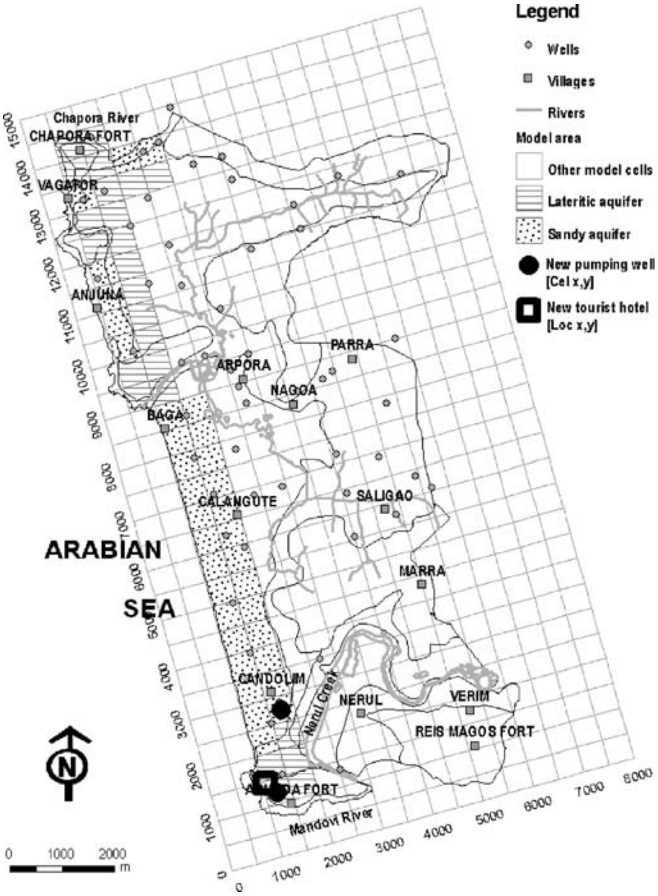

Fig. 12 Case study 2 ($Loc_{1100,1500}$)

The results obtained for the second scenario (Fig. 11) show that the cells retained to supply the tourist hotel are the nearest ones. The difference between the flow rate pumped in each one results from having $Z_{1750,6250}$= 8.1 m and $Z_{1750,5750}$=9.98 m. So, as expected, the highest flow rate is pumped from the cell presenting the smallest pumping groundwater head (the influence coefficients are the same for both cells) in order to lower energy costs.

The results obtained for the third scenario (Fig. 12) show that $Cel_{1750,2750}$ and $Cel_{1250,1250}$ will provide the required flow. Even if $Cel_{1250,2250}$ is the nearest cell, choosing it would imply the choice of a third cell to satisfy the total demand. In fact, the constraints derived from Fig. 8, indicate $Q_{1250,2250\mathrm{max}}$=400 m^3/d, and the pumped flow rate in cell $Cel_{1250,1250}$ already gives a drawdown of 13.08 m. So, choosing $Cel_{1250,2250}$ would increase the cost, not only because this cell is near the shore, but also because the possibility of taking into account economies of scale is dismissed.

Conclusions

After the characterization of the Bardez zone, based on the available hydrogeological and socio-economic data, optimization models aimed at determining the water needs of future tourist resorts located in the coastal zone of Bardez were developed. These models take into account the risk of saline intrusion. One of the most interesting inputs of this study was the original results obtained by the research accomplished during the COASTIN Project (Measuring, monitoring and managing sustainability: the coastal dimension) on the relation between safe extraction rates and the required minimum distance to the coastline, in order to avoid saltwater intrusion in the pumping wells (Lobo-Ferreira et al. 2002).

The optimization models were applied to different exploration scenarios. The results indicated that the best location for the wells, if permitted to operate within their drawdown limitations, are the cells a long way from the shore. If cells located near the shore are chosen, the costs increase, because scale economies are dismissed.

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