Numerical simulation of the influence of management alternatives of a projected reservoir on a small alluvial aquifer affected by seawater intrusion (Almuñécar, Spain)

F. Padilla · J. Benavente · J. Cruz-Sanjulián

Abstract The present study concerns the application of a numerical approach to describe the influence of anthropogenic modifications in surface flows (operation of a projected reservoir) on the freshwater-seawater relationships in a downstream coastal aquifer which has seasonal seawater intrusion problems (River Verde alluvial aquifer, Almuñécar, southern Spain). A steady-state finite element solution to the partial differential equation governing the regional motion of a phreatic surface and the resulting sharp interface between fresh water and salt water was used to predict the regional behavior of the River Verde aquifer under actual surface flow conditions. The present model approximates, with simple triangular elements, the regional behavior of a coastal aquifer under appropriate sinks, sources, Neumann and open boundary conditions. A steady-state solution to this numerical approach has been shown to precisely calculate freshwater heads, saltwater thicknesses, and freshwater discharges along steeply sloping coasts. Hence, the adequate treatment and interpretation of the hydrogeological data which are available for the River Verde aquifer have been of main concern in satisfactorily applying the proposed numerical model. Present simulated conditions consider steady-state yearly averaged amounts of external supplies of fresh water in order to determine the influences of the projected Otívar reservoir on the further behavior of the River Verde coastal aquifer. When recharges occur at the coastline, essentially because of freshwater deficits due to groundwater overexploitation, a hypothesis of mixing for the freshwater-saltwater transition zone is made in order to still allow the model to continue calculating groundwater heads under the sea level, and, as a consequence, the resulting seawater intrusion and recharges of saltwater from the sea. Simulations show that a considerable advance in seawater intrusion would be expected in the coastal aquifer if current rates of groundwater pumping continue and a significant part of the runoff from the River Verde is channeled from the Otívar reservoir for irrigation purposes.

Key words Coastal aquifer · Sharp interface · Salt water · Transition zone · Boundary conditions · Open boundaries · Finite elements · Freshwater balance · Freshwater recharge · Freshwater deficit

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Introduction

The basin of the River Verde (flowing into the Mediterranean Sea from Granada, Spain) has a surface area of 104 km^2, approximately half of which corresponds to the head section, made up of Triassic carbonate materials (calcareous and dolomitic marble). The rest of the basin is predominantly metapelitic (quartzite schists and mica schists, which are mainly Paleozoic). The alluvial aquifer from the River Verde is enclosed within these materials. This aquifer, in spite of its small size (less than 4 km^2), is of great interest, especially from an economic and scientific point of view.

Its economic interest is due to its situation in an area in which climatic characteristics make irrigated agricultural products highly profitable. Protection from cold north winds by an important mountain range prevents the risk of winter frosts, cloudy days, etc. The temperatures are mild with mean monthly values ranging between 12 °C in January and 24 °C in August. The crops which predominate in the area are of a subtropical type: mainly avocados and custard apples, both fairly rare on the European continent. Tourism is another important economic activity in the area, concentrated particularly in the coastal town of Almuñécar during the summer period, when the normal population of 20 000 is quadrupled. Both activities require a supply of good quality water.

Until around the 1960s, the water necessary for irrigating the approximately 4 km^2 of crops situated on the alluvial plain of the River Verde was obtained directly from the river. Since then, the agricultural transformation of the area has extended to cover more land, previously dedicated to forestry or grazing, situated on the mountainsides of the fluvial valleys which has been adapted to its new use by terracing. The water derived from the River Verde is clearly insufficient for the irrigation of these new crops which currently cover a surface area of around 20 km^2. For this reason, a great majority of the water to irrigate them is obtained from numerous wells which pump water from the alluvial aquifer of the River Verde.

The area has a Mediterranean climate in which precipitation is generally very scarce between June and September. It is precisely during this period that the water requirements for irrigation and human consumption are at their peak and thus, when pumping from the alluvial aquifer is most intensive.

The first detailed hydrogeological studies carried out in the area (Benavente 1982) highlighted the evident risk of seawater intrusion, taking into account the extreme seasonal overexploitation and the piezometric data available. This process was noted in the summer of 1982 and, to a greater extent, in the summer of 1983. The affected wells situated over 1 km from the coastline, in particular those for the water supply to Almuñécar, revealed rapid increases in the chloride content of the pumped water, rising from under 20 mg/l to over 5 g/l (Benavente and others 1984).

The main peculiarity of the process was the unusual speed at which the desalinization of the aquifer occurred once the summer season was over, that is when pumping was reduced considerably. This prompted studies during the following years in which the salination-desalination pattern repeated itself (Fernández-Rubio and others 1986; Fernández-Rubio and Jalón 1988). Additionally, a series of boreholes was made for creating a hydrochemical and piezometric monitoring network in the aquifer. The information derived from these boreholes made it possible to gain a greater knowledge of the geometrical and hydraulic characteristics of the aquifer (Benavente and Calvache 1988).

The next phase of the research was based on numerical modeling of the aquifer, both of the groundwater flow and the contact zone between fresh water and salt water (Calvache and Pulido 1990, 1991). The models used were MODFLOW (McDonald and Harbaugh 1988), MOC-DENSE (Konikow and Bredehoeft 1984) and BADON2 (Verruijt 1987). This research contributed to improving the quantitative knowledge on how the aquifer functioned, especially as regards the characterization of the seasonal overexploitation. It also confirmed the intensification of the seawater intrusion below the points with the highest pumping rate.

Artificial recharge was among the techniques suggested as a possible way of resolving the problem of seawater intrusion (Calvache and Pulido 1990), but others have been also proposed: diversion of resources from nearby basins, construction of an impermeable trench near the coastline and creation of a reservoir in the head section of the River Verde. The latter, which is currently at the planning stage, aims to supply water for human consumption and agricultural irrigation by means of gravity and, consequently, to reduce pumping from the aquifer.

The need to obtain a preliminary estimate of the effect the planned Otívar reservoir may have on the aquifer (and in particular on the interface between fresh and sea water) has prompted a new phase of numerical modeling research, although this time particularly using a new approach based on open boundary conditions to the steady numerical solution of seawater intrusion (Padilla and others 1990, 1997;Padilla and Cruz-Sanjulián 1997). The main advantage is that, for practical problems involving steeply sloping coasts, seawater intrusion and freshwater discharges at the coast can be correctly calculated for a stationary regime by exclusively solving a single-phase equation of freshwater movement through a porous media.

To address this, the main hydrogeological characteristics of the River Verde basin are summed up, giving particular attention to the alluvial aquifer. In order to verify the actual behavior of the unconfined coastal aquifer the applied finite element model gives a solution to a steady-state problem. Actual external supplies of fresh water are averaged yearly as sources from net rainfall and return flows, sinks from pumping wells, as well as freshwater recharges from neighboring watersheds. The simulations are designed to estimate the behavior of the alluvial aquifer of the River Verde under the influence of surface flows coming from the water management of the Otívar reservoir. The simulations give results for freshwater discharges (positive total freshwater balances) and seawater recharges (negative total freshwater balances) at the coastline due to global surplus or deficits of fresh water. Results show reasonable calculations of freshwater heads, interface depths and thicknesses of fresh water and salt water, a probable transition zone of mixing between fresh and salt waters, as well as precise amounts of freshwater discharges and seawater recharges along the coastline.

Brief description of the numerical model

The flow in phreatic coastal aquifers of large horizontal extent, compared to their thickness, may be assumed to result in variations of the groundwater head in a vertical direction so small that they can be ignored. This assumption leads to the two-dimensional averaged equation of freshwater flow in a horizontal plane. Considering, in addition, salt water in equilibrium with the sea level and the existence of a sharp freshwater-saltwater interface below a less dense freshwater (Fig. 1), the two-dimensional

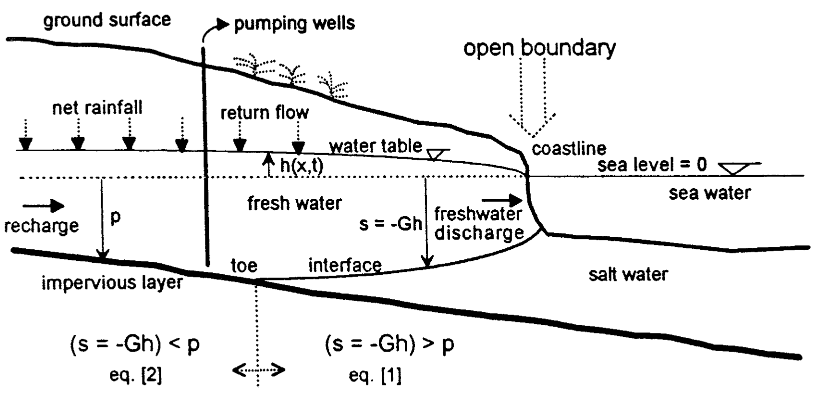

Fig. 1
Vertical schematic section of a phreatic coastal aquifer

equations that govern the motion of fresh water in an unconfined coastal aquifer can be written as follows (Shamir and Dagan 1971):

$$(n_f + n_s G)\,\frac{\delta t}{\delta t} = \frac{\delta}{\delta x}\left(K_{xx}(h-s)\,\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta x}\left(K_{xy}(h-s)\,\frac{\delta h}{\delta y}\right) + \frac{\delta}{\delta y}\left(K_{yx}(h-s)\,\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(K_{yy}(h-s)\,\frac{\delta h}{\delta y}\right) + Q \quad \text{if } (s=-Gh)>p \tag{1}$$

$$n_f\,\frac{\delta h}{\delta t} = \frac{\delta}{\delta x}\left(K_{xx}(h-p)\,\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta x}\left(K_{xy}(h-p)\,\frac{\delta h}{\delta y}\right) + \frac{\delta}{\delta y}\left(K_{yx}(h-p)\,\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(K_{yy}(h-p)\,\frac{\delta h}{\delta y}\right) + Q \quad \text{if } (s=-Gh)<p \tag{2}$$

where, taking sea level as the reference, h is the freshwater head (positive above sea level), s is the level of the saltwater interface (negative below sea level), n_f and n_s are the effective porosities for the movement of the phreatic surface and the interface, respectively, Q is the net source (positive) or sink (negative) from the surface of the aquifer in volumetric flow of water per surface unit, and K_{ij} is the hydraulic permeability tensor in the freshwater zone. For unconfined coastal aquifers, the Ghyben-Herzberg principle approximates the position of the saltwater interface in equilibrium with the seawater level by the following relationship:

$$s = -\frac{{}_{f}}{{}_{s} - {}_{f}}\,h \quad \text{if } (s=-Gh)>p$$

$$s = p \quad \text{if } (s=-Gh)\leq p$$

where, $G=\frac{{}_{f}}{{}_{s}-{}_{f}}$, ${}_{f}$ and ${}_{s}$ are the densities of fresh and salt waters, respectively, and p is the height of the impervious substratum of the aquifer (below or above sea level, corresponding to negative or positive values, respectively). Thus, the mathematical model is represented by Eq. 1 when seawater intrusion interacts vertically with fresh water, and by Eq. 2 otherwise, that is, when only freshwater flow is vertically averaged.

It is important to note that the above basic equations correspond to a classical regional model of seawater intrusion in equilibrium with the seawater regional level (Bear and Verruijt 1987). What it is not classical are the boundary conditions which are used to solve them numerically. Open boundary conditions at a steep coast are numerically necessary in order to find the correct groundwater solutions resulting from freshwater discharges or recharges at the sea level (Padilla and Cruz-Sanjulián 1997). The latter can be described, for a steeply sloping coast, by the Dupuit approximation which considers horizontal flow and the interface position as also being horizontal in the proximity of the coastline. This kind of boundary can be precisely monitored by the numerical resolution procedure related to the finite element method. Calculated freshwater heads along and in the proximity of the coastline do not need to be the same as the sea level. Hence, for example, a saltwater interface deeper than the seawater level could occur at the coastline, in agreement with the Ghyben-Herzbeg principle, as a consequence of the calculated positive freshwater heads resulting from the application of the numerical model when positive freshwater balances and discharges to the sea take place in the aquifer.

Inversely, when negative groundwater balances can occur inside the coastal aquifer, owing for instance to freshwater overexploitation, a hypothesis of freshwater-saltwater mixture is needed in order to still allow the calculation of groundwater heads below the sea level. As a consequence, the corresponding seawater intrusion and recharges of a freshwater-saltwater mixture from the sea can also be calculated at a coastline which is treated with open boundary conditions. Hence, open boundary treatment allows also the calculation of recharges of saltwater from the sea provided that a reasonable hypothesis of mixing is made. For the present numerical applications, when there is locally or globally a freshwater deficit, and in the absence of other experimental data, it is assumed that the thickness of the transition zone of mixing between freshwater and saltwater could be approximately equivalent to the drawdown reached locally under the height of the sea by the water level, plus a constant value taken as the thickness of this transition zone at the coastline. This last value can be used, if desired, as a parameter of adjustment in order to obtain calculated water levels which are not very dissimilar from the height of the sea at the coastline. Adequate steady-state solutions to this approach can be obtained without difficulty with the help of a prior simulation for an arbitrary thickness of the transition zone at the coastline, if recharges of a freshwater-saltwater mixture from the sea are needed in order to compensate a global deficit in the freshwater balance of the aquifer. The present finite element approach allows this procedure to give very satisfactory results as described in the conditions of simulation for the practical applications to the River Verde coastal aquifer.

Hydrogeology of the River Verde basin

The head of the River Verde basin (sub-basins of the River Verde and River Lentegí) is mainly made up of permeable carbonate rocks from the Middle to Upper Trias. These include calcareous and dolomitic marble, which is sometimes very fissured, and whose total thickness can reach over 1000 m. Relatively important metapelitic intercalations exist according to the particular sector, which together with fractures can individualize various flow systems within the head basin drained by springs at different altitudes (Fig. 2).

The input from the majority of the head sector of the River Verde can be quantified from records kept at the Cázulas gauging station. For the period 1969–1970 to 1988–1989, a mean flow of almost 13.5 hm^3/year ($1\ hm^3 = 10^6\ m^3$) is obtained, with approximate mean monthly values ranging between 1.7 hm^3 (January) and 0.7 hm^3 (September). The analysis of the hydrograms reveals not very sharp rises after the main pluviometric episodes and relatively high minimum levels of water flows. This behavior reflects the important regulating effect of the subterranean flow through the fissured carbonates of the aquifer. In fact, it is estimated that the subterranean contribution represents approximately 80–90% of the mean inputs in the gauging station (Dirección General de Obras Hidráulicas, unpub. data 1991).

The eastern extreme of the head sector corresponds to the basin receiving water from the River Lentegí, which joins the River Verde only a short distance downstream from the Cázulas gauging station (Fig. 2). In the River Lentegí basin, there are no gauging stations, although from sporadic measurements it has been confirmed that the discharge in its final extreme is in the order of 100 l/s (approx. mean value), with a regulating effect similar to that indicated for the River Verde. In this basin, significant springs also exist at different altitudes, a reflection of the compartmentalization of the carbonate aquifer, in which part of its resources may drain underground towards other limiting basins to the northeast (Dirección General de Obras Hidráulicas, unpub. data 1991).

The alluvium of the River Verde occupies a surface area of some 3.5 km^2. It begins to be well represented downstream from the confluence of the rivers Verde and Lentegí, near the village of Otívar, at an altitude of slightly over 120 m. From there to the mouth of the river, alluvium appears bounded by materials of a thick metapelitic sequence (basically micaschists and quartzites) which constitute the impermeable substratum of the alluvial aquifer. Most of the lateral borders of the aquifer are the result of fairly vertical mechanical contacts (fractures).

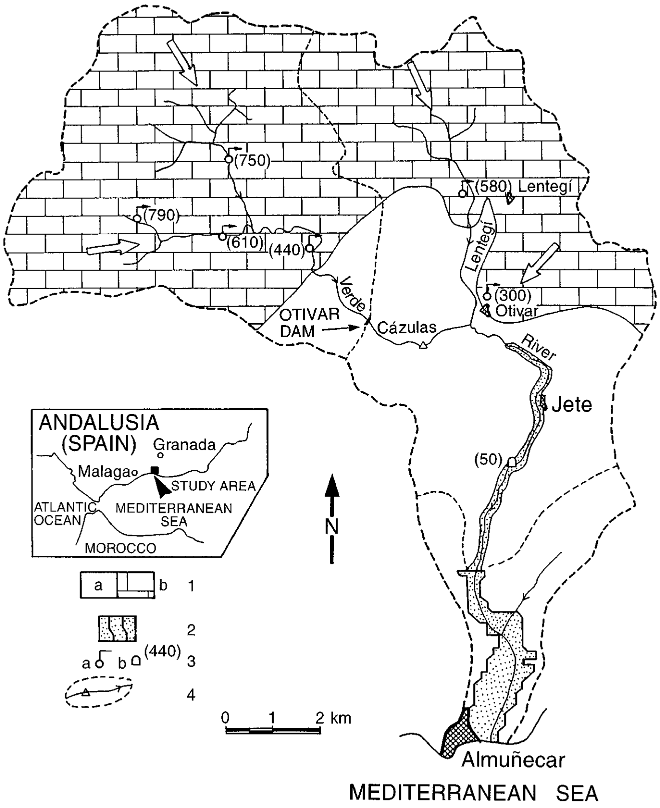

Fig. 2
Situation and hydrogeological sketch of the study area [(*1*) *a* Paleozoic schists and *b* Triassic carbonate rocks (*arrows* indicate main groundwater flow directions); (*2*) River Verde alluvial aquifer showing the modeled southern section; (*3*) *a* spring and *b* gallery with altitude (in brackets); (*4*) Main streams and gauging station, basin and subbasin boundaries]

The majority of the aquifer corresponds to the so-called "Vega" (irrigated plain) of Almuñécar, which covers an area from an altitude of 40 m to sea level and coincides with an appreciable widening of the fluvial valley with respect to the sector situated upstream (Fig. 3).

From the information obtained from numerous existing wells and specific borehole drilling campaigns it has been shown that (a) in most of the "Vega de Almuñécar" sector, the substratum is located at depths between 30 m and 70 m; and (b) that the northern boundary of this sector coincides approximately with the intersection between the substratum and sea level (0 m).

Measured data on permeability and porosity are scarce. Pumping tests in the Vega de Almuñécar (Benavente 1982; Calvache and Pulido 1990) give transmissivity val-

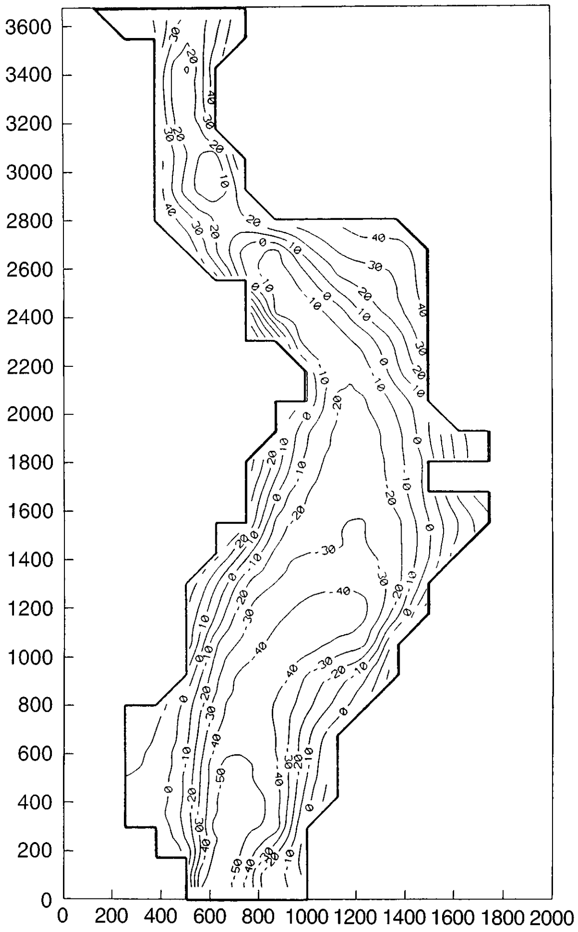

Fig. 3
Contour map of the altitudes (m) of the impervious substratum of the modeled part of the River Verde alluvial aquifer

ues of over 30000 m^2/day. According to the thickness of the saturated aquifer in this sector, the permeability of the aquifer should range between 200 and 1000 m/day. Permeability values of the same order of magnitude were obtained by Benavente and Calvache (1988) from the analysis of the granulometric characteristics of the materials obtained by a series of reconnaissance boreholes. In accordance with this same information, effective porosity values, mainly within the 15–20% range, were obtained. Although in other studies lower values are suggested, of the order of 5%, based on the value of hydraulic diffusivity as a result of the analysis of the tidal influence on the aquifer (Calvache and Pulido 1991).

Prior to the 1980s, the flow in the gallery of Las Angosturas, which is located approximately 1 km downstream from Jete (Fig. 2), must have been continuous and with values generally ranging between 200 and 400 l/s. In the last ten years, it has not generally reached more than 150 l/s and dries up during the summer months. Only after the important precipitation in November and December of 1989 did it once again measure flows of over 400 l/s, but these later decreased very rapidly.

The inland penetration of the interface does not seem to have occurred in an extensive and homogenous front, but rather in a localized way, taking advantage of the more permeable layers. In turn, at those points where there exists a more continuous exploitation, such as those wells supplying Almuñécar and situated above the tongue of penetration of the interface, vertical intrusion of salt water has been identified. In previous studies (Fernández-Rubio and others 1986; Dirección General de Obras Hidráulicas – Junta de Andalucía, unpub. data 1988) the existence of important variations in the salinity of the groundwater has been revealed, affected to differing extent by the seawater intrusion, in such a way that it must sometimes be considered an opposing process, which is to say, saltwater extrusion. This process is enhanced by periods in which recharge is greater than exploitation; that is, when the pluviometric and fluvial inputs are higher and when the greatest piezometric rises are recorded.

The recharge from precipitation on the permeable outcrops is not very significant. It is estimated that the actual evapotranspiration is on the order of 90% of the precipitation, which has an annual mean of slightly more than 450 mm. Another source of recharge, which is also difficult to assess, arises from the return flow of irrigation on alluvial materials, which is mainly water derived from the River Verde. The majority of the resources of the alluvial aquifer comes from seepage of River Verde streamwater, specially in its upper section (Otívar-Las Angosturas gallery).

In contrast to the recharges, which usually have various sources that are difficult, on the whole, to quantify, the discharges from the aquifer are basically of two types: pumping and subterranean discharge into the sea. With regard to the groundwater pumping, used for human consumption and irrigation (especially on the terraces which cover most of the impermeable slopes of the alluvial valley) their magnitude is variable according to the hydrometeorological characteristics of each particular year. They may be estimated as ranging from 7 to 11 hm^3/year, from the information available from the various surveys carried out. Figure 4b shows the location of the main extraction points.

The subterranean discharges into the sea have been mainly calculated from yearly averaged water balances in the aquifer. This was done in previous studies (Benavente 1982; Calvache and Pulido 1990; DGOH-JA, unpub. data 1988). According to the results obtained, total discharges of 3–6 hm^3/year may be expected, under average hydrological conditions. Naturally, most of this discharge is concentrated in the winter-spring period. Summing up, the mean resources of the alluvial aquifer of the River Verde can be quantified at around 14 hm^3/year, according to the various records reviewed. In turn, the proposed conditions of simulation outlined below, corresponding to yearly averaged water balances of the River Verde basin, may be considerably modified during wet years or severe droughts.

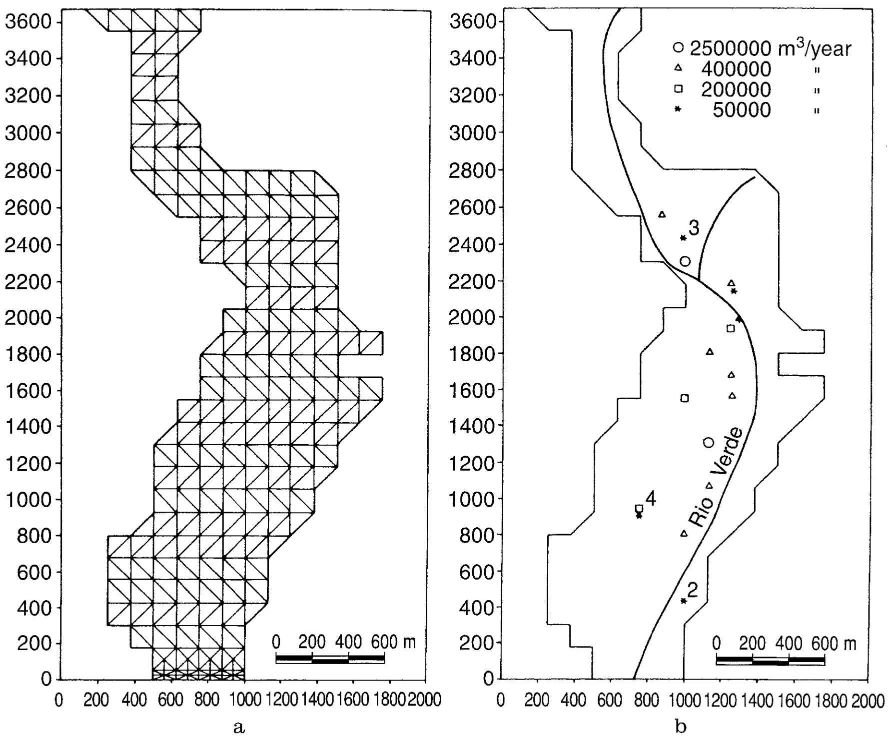

Fig. 4
a Finite elements discretization of the River Verde coastal aquifer, and **b** yearly averaged freshwater withdraws from pumping wells as used in the numerical simulations of the groundwater regime of the River Verde aquifer.

Numerical application to the River Verde aquifer

The aquifer was discretized with a regular grid of isoscefes triangles, although in the southern sector, near the coastline where fresh water is discharged into the sea, a finer grid was designed in order to simulate the position of the interface as accurately as possible (Fig. 4a). This zone is governed by important nonlinearities and by the particular treatment of the outflow open boundary. The phreatic level has not been imposed as a condition at the model's boundaries, not even at the southern boundary between the aquifer and the sea which was treated with open boundary conditions. The simulations were carried out in a stationary regime, with a view towards establishing how the aquifer of the River Verde functions. All the simulation conditions in the examples presented were elaborated from the hydrogeologic parameters, recharge and exploitation values described below. The aquifer porosity and permeability values used in the modeling were obtained from the interpretation of pumping tests and granulometric analyses in previous studies (Benavente and Calvache 1988; Calvache 1989).

In order to evaluate the recharge and exploitation of the aquifer, very different data from diverse authors were used. In particular, pluviometric and surface flow gauging data were obtained from the Otívar Dam project (Velasco and others 1984). The gauging carried out has made it possible to estimate the mean input of the River Verde to the planned reservoir as 15.8 hm^3/year. An amount of 5.5 hm^3/year must be subtracted from this figure, which is the volume of water that an electric company extracts from the river. This water is returned to the river downstream from the planned dam. Thus, the mean flow that would be regulated by the reservoir is 10.3 hm^3/year (Table 1).

The aquifer is currently subject to intense exploitation by wells. Although the volume of water extracted in the various wells is variable depending on the time of year, averaged annual flows of -10 hm^3/year (Instituto Geológico y Minero de España, unpub. data 1987; Calvache 1989) have been used, which represent the annual mean of all the water drawn by pumping (Table 1). In this regard, we have grouped the wells by situation and by category, with a view to totaling their flows and making their situation coincide as far as possible with the nodes corresponding to the spatial discretization of the aquifer (Fig. 4b).

Between the planned Otívar reservoir and the alluvial aquifer, the River Verde has some small tributaries flowing into it, the most important of which is the River Lentegí. Due to the particular hydrogeologic characteristics of the Lentegí subbasin, the yearly averaged total inflow in this section is estimated to be approximately 2 hm^3/year.

The main irrigation channels have their intakes between Otívar and Jete. They divert a mean of –5 hm^3/year for crops over the aquifer, approximately 20% of which (1 hm^3/year) is supposed to recharge the alluvial aquifer in the form of return flow. A similar amount (1 hm^3/year) is estimated for the return flow to the aquifer from crops located in the valley slopes, irrigated with the waters pumped from the alluvial aquifer. In these type of crops, the return percentage is smaller than the previous figure, but this is balanced by the larger surface of terraced cultivations. Net rainfall on the aquifer outcrops

Table 1
Mean annual volumes used for the numerical simulations of the Ríver Verde coastal aquifer

Mean annual volumes (hm^3/year)	Application 1	Applicaton 2	Application 3
Total freshwater balances (A + B + C + D)	+5	+1	−1
A) Recharges from small catchment basins	0.1	0.1	0.1
B) Return flows and net rainfall	2.1	2.1	2.1
C) Pumping wells	−10	−10	−10
D) Recharges from River Verde (a + b + c + d)	12.8	8.8	6.8
a) Otívar reservoir	10.3	6.3	4.3
b) Electric company	5.5	5.5	5.5
c) Lentegí subbasin	2	2	2
d) Irrigation channels	−5	−5	−5

and contributions from small catchmentbasins, situated in the lower section of the River Verde and which flow directly into the alluvial aquifer, also contribute to the recharge of the system. Both contributions are small (0.1 hm^3/year). Then, a joint recharge of 2.1 hm^3/year, from net precipitation and return flows, was distributed homogeneously over all the nodes corresponding to the spatial discretization of the River Verde aquifer.

In conclusion, the surface contributions to the aquifer in the upper section of the River Verde can be estimated as having a mean value of 12.8 hm^3/year. Once the Otívar dam is built, this flow would diminish by losses caused by evaporation from the reservoir and the water channeled by the dam for irrigation and human consumption, such that the circulating flow will depend on the management of the reservoir. In the simulation examples which are given in the Table 1, recharge values of approximately 10.3, 6.3 and 4.3 hm^3/year have been used.

In the first example, the aim was to reflect the importance of the mean annual exploitation on the regimen of the aquifer in its natural state. As indicated above, the pumping locations were considered and grouped according to their importance (Figure 4b). The total amount of water pumped amounts to the annual mean calculated, that is –10 hm^3 (Example 1: water balance +5 hm^3/year).

In the second example, the influence of the flows originating from the Otívar dam are reflected in the state of the aquifer subject to exploitation. For this purpose, a level of flow regulation by the reservoir which would result in a positive, but reduced, water balance was considered (Example 2: water balance +1 hm^3/year, circulating flow in the river downstream from the Otívar dam = 6.3 hm^3/year). In the third simulation example, the water balance is negative: water balance = –1 hm^3/year, with a circulating flow in the river downstream from the Otívar dam of 4.3 hm^3/year.

Discussion and results

The results of the simulations have been represented according to their three main characteristics, that is, watertable levels, the position of the interface between salt and fresh waters and the thicknesses of fresh water and salt water available in the aquifer. Figures 5 and 6 illustrate the contour maps of the simulation results for the two horizontal dimensions of the unconfined aquifer of the River Verde. The results obtained are illustrative of the evolution of the state of the aquifer for the different freshwater balances (+5 hm^3/year, +1 hm^3/year and -1 hm^3/year) which, in turn, represent different management alternatives for the operation of the reservoir.

In the contour maps representing the interface (Fig. 6), the area occupied by the interface and the contour lines of the freshwater and saltwater thicknesses are shown. The boundaries of the inland area allocated to the interface on the map represent the zero saltwater thickness (interface toe); beyond these limits, the contour lines represent the thickness of fresh water only. The sector occupied by seawater intrusion has similarly been illustrated when its presence is apparent in the simulation results. In this regard, seawater intrusion is considered to exist where the freshwater thickness is nil and where the position of the interface coincides with that of the watertable level. For the purpose of obtaining a Ghyben-Herzberg theoretical approximation and a steady-state solution, the sector occupied by seawater intrusion naturally coincides with that occupied by the phreatic levels below sea level (negative).

The effect of various management alternatives for the reservoir on watertable levels, thickness of fresh water and the position of the interface was considered. In this regard, Fig. 5 and 6 illustrate the results of the simulation examples 1, 2 and 3 for different water balances (+5, +1 and –1 hm^3/year). These balances are mainly a consequence of natural recharge, pumping exploitation and flow regulation operations by the Otívar dam. The contour maps illustrate the possible evolution of the successive states reached by the aquifer in a stationary flow regime. It can be seen, for example, that when the water balance is negative (–1 hm^3/year), the aquifer shows clear signs of seawater intrusion, mainly due to overexploitation of existing groundwater resources. As is to be expected, this implies that if current rates of groundwater exploitation continue, and an important part of the input from the River Verde is extracted as a result of the water being stored in the reservoir (or eventually channeled),

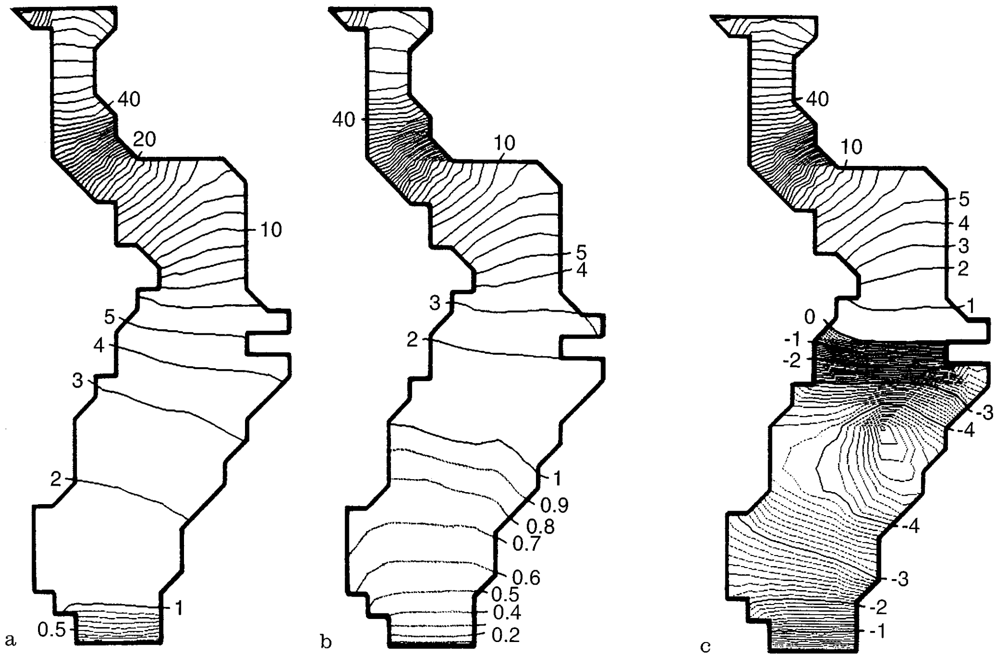

Fig. 5
Contour maps of the altitudes (m) of the water table for the steady-state simulations considering freshwater balances of **a** +5 hm^3/year, **b** +1 hm^3/year, and **c** -1 hm^3/year

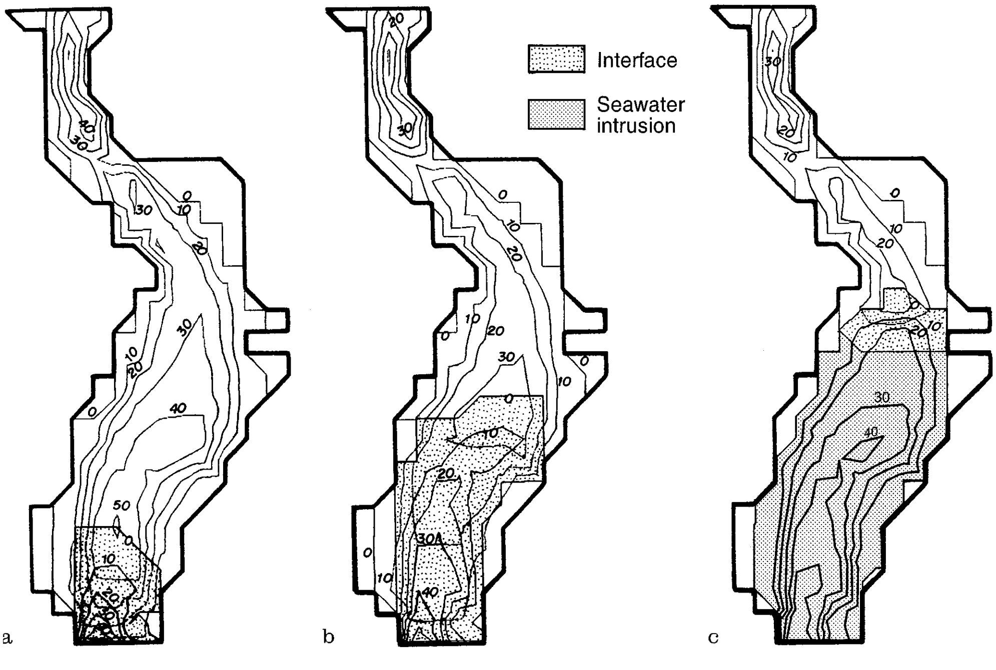

Fig. 6
Contour maps of the freshwater (----) and saltwater (–) thicknesses (m) for the steady-state simulations considering freshwater balances of **a** +5 hm^3/year, **b** +1 hm^3/year, and **c** -1 hm^3/year

this would produce a considerable advance in seawater intrusion. It is therefore necessary to bear this circumstance in mind in the rational management of the reservoir, such that, in order to prevent a severe advance in the interface, a clearly positive water balance must be maintained, as suggested in previous paragraphs, that is, allowing the circulation of sufficient flow into the River Verde downstream from the dam.

These results may serve to approximate the possible impact of the reservoir on the availability of freshwater in the aquifer. Obviously, a multitude of other possible alternatives are open to simulation, in which for example recharge, exploitation, regulation, etc. could be included. In this way, the influence of the conditions imposed on the hydrogeological regime of the aquifer could be estimated. Similarly, it would be possible to simulate other more complex situations, such as the evolution of the aquifer according to varying transient recharges, exploitation and regulation, etc.

Main conclusions

This research has provided numerical simulations of the influence of surface flows, coming from the water management of the projected reservoir of Otívar, on the regional groundwater behavior of the River Verde coastal aquifer (Almuñécar, Granada, Spain). A single-phase two-dimensional finite element model, considering open boundary conditions for steep coasts and a sharp interface between freshwater and saltwater, was applied in steady-state conditions to the phreatic aquifer for freshwater surplus and deficits at the coastline. When recharges of saltwater can occur at the coastline, essentially because of freshwater deficits, a hypothesis of mixing for the freshwater-saltwater transition zone allows the model to calculate the resulting seawater intrusion in the River Verde alluvial aquifer. Hence, the adequate treatment and interpretation of the hydrogeological data which are available for the coastal aquifer were of main concern in satisfactorily applying the proposed numerical model. To this issue, yearly averaged amounts of external supplies and withdraws of freshwater in the aquifer were necessary in order to determine the influence of the surface flows, that would come from the projected dam of Otívar, on the further behavior of the coastal aquifer of River Verde. Results of the steady state simulations showed reasonable calculations of the watertable levels and the freshwater and saltwater thicknesses, as well as, the extents of the interface and seawater intrusion into the aquifer for the correct total discharges or recharges along the coastline. As a result of the present hydrogeological simulations on the phreatic aquifer, a considerable advance in seawater intrusion would be expected in the River Verde coastal aquifer if current rates of groundwater exploitation continue and an important part of the fresh water from the River Verde is annually channeled from the Otívar reservoir for irrigation purposes.

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