Numerical modelling of surfacewater/groundwater flows for freshwater/saltwater hydrology: the case of the alluvial coastal aquifer of the Low Guadalhorce River, Malaga, Spain

Abstract
This applied research deals with the numerical modelling and transient simulation of the joint surfacewater/groundwater flows that characterize the freshwater/saltwater hydrology of the coastal alluvial valley of the Low Guadalhorce River, Malaga, Spain. The MELEF model used was mainly adapted and calibrated for a simulation period of two hydrological years 1989/1990–1990/1991, before the current channelling of the river, where floods and low precipitations have been recorded. The model calibration process was performed with the aid of phreatic levels measured in numerous wells and piezometers, as well as recharges from precipitation and irrigation on the alluvial surface, which was also assessed by the hydrologic model SSMA-2. The present numerical approach can predict the forthcoming hydrology of the coastal alluvial of the Guadalhorce River after its final channelling.
Numerical modelling of surfacewater/groundwater flows for freshwater/saltwater hydrology: the case of the alluvial coastal aquifer of the Low Guadalhorce River, Malaga, Spain

Francisco Padilla · Ana Méndez · Rafael Fernández · Pablo R. Vellando

Received: 1 February 2007 / Accepted: 30 July 2007 / Published online: 15 September 2007 © Springer-Verlag 2007

Abstract This applied research deals with the numerical modelling and transient simulation of the joint surfacewater/groundwater flows that characterize the freshwater/saltwater hydrology of the coastal alluvial valley of the Low Guadalhorce River, Malaga, Spain. The MELEF model used was mainly adapted and calibrated for a simulation period of two hydrological years 1989/1990-1990/1991, before the current channelling of the river, where floods and low precipitations have been recorded. The model calibration process was performed with the aid of phreatic levels measured in numerous wells and piezometers, as well as recharge from precipitation and irrigation on the alluvial surface, which was also assessed by the hydrologic model SSMA-2. The present numerical approach can predict the forthcoming hydrology of the coastal alluvial of the Guadalhorce River after its final channelling.

Keywords Coastal aquifer · Groundwater/surfacewater · Numerical modelling · Saltwater/freshwater · Guadalhorce drainage basin (Spain)

Introduction

Two studies were carried out on the Guadalhorce alluvial aquifer, where two models were developed on groundwater flow respectively (DGOM-MOPU 1986; ITGE 1995/1996). These models have similar working characteristics but different specific particularities. First of all, both models consider only groundwater flow and do not properly take into account the saltwater flow of coastal aquifers.

Nowadays, there is an increasing need for integrated surfacewater and groundwater-distributed modelling. The philosophy and role of distributed hydrological models in water resources have been described by Abbot and Refsgaard (1996). MIKE SHE and MIKE BASIN are the two examples of distributed and physically based modelling systems developed by DHI (1995, 1997) for describing the major flow processes of the entire land phase of the hydrologic cycle. Recent methodologies were also developed on combined watershed and groundwater applications to all the water resources of a particular river basin (Chiew et al. 1992; Sophocleous and Perkins 2000; Ross et al. 2005).

In this field and with respect to applications of integrated surfacewater and groundwater models (Ross et al. 2005; Sophocleous and Perkins 2000), a new methodology of finite element modelling has been developed and applied (MELEF model, “Modèle d’Éléments Finis” in French) which considers joint surfacewater and groundwater regional flows, in addition to the effects of saltwater intrusion from the sea by means of an immiscible saltwater-freshwater interface. Using this methodology in the modelled drainage basin, it is possible to assess the saltwater flow from the sea, the drainage layout of surface runoff and the freshwater levels, as well as the flow and thickness of surface and groundwaters (Padilla and Cruz-Sanjuán 1997; Padilla 1999; García-Aróstegui et al. 2000; Padilla and Méndez 2002).

First of all, the present conceptual model of the Low Guadalhorce hydrographic watershed (Méndez et al. 2003)
aims to consider the joint flow of surface and groundwaters in the quaternary alluvial under study between the city of Alora and its drainage outlet into the Mediterranean Sea. The geological materials of the alluvial aquifer have certain lithologic heterogeneities where it is quite frequent to find paleochannels filled with coarser detrital sediments which do not coincide with the present riverbed. This alluvial unconfined water-table aquifer does not reach 50 m thickness and has a surface area of 86 km² (Linares et al. 1995). In this respect, the numerical modelling of the surface and groundwater flows in the quaternary alluvial aquifer requires the following hydrologic data: hydraulic conductivity, porosity, impervious substratum location and detailed topography of the modelled sector.

Modelling the joint flow of surface and groundwaters is particularly interesting in this case because it concerns the assessment of groundwater/surfacewater relations in a coastal freshwater/saltwater aquifer like the alluvial of the Low Guadalhorce River. On the one hand, in this respect and from the standpoint of the numerical conceptual model MELEF, water inlets to the modelled system need to be properly assessed. On the other hand, outflows are related to known water usages (water pumping and diversion) as well as to the unknown drainage outlets, such as evaporation from free water bodies, evapotranspiration from the alluvial soil and freshwater discharges to the Mediterranean Sea.

For this purpose, the MELEF model was oriented to simulate the joint transient freshwater and groundwater flows in the coastal alluvial of the Low Guadalhorce River, which in the past has experienced severe seawater intrusion problems due to overexploitation of freshwater during the drought period of 1994 and 1995. Furthermore, the numerical model considers the spatial and temporal distribution of evapotranspiration over the entire modelled sector and water interactions between the unconfined aquifer and the river during a particular hydrological event.

Conceptual model

In coastal aquifers, there is generally a hydraulic gradient towards the sea that serves as a recipient for their excess freshwater. Owing to the presence of seawater in the aquifer formation beneath the sea bottom, a contact zone is formed between the lighter freshwater flowing to the sea and the heavier, underlying seawater. Freshwater and seawater are actually miscible fluids and therefore the contact zone between them takes the form of a transitional zone caused by hydrodynamic dispersion. Across this zone, the density of the mixed water varies from that of freshwater to that of seawater. However, under certain conditions, the width of this zone is narrow, in relation to the thickness of the aquifer, so that the zone of gradual transition from freshwater to seawater may be approached as a sharp interface (Fig. 1).

Assuming an essentially static equilibrium and horizontal flow, with a hydrostatic pressure distribution in the freshwater region and a stationary distribution in the seawater, the interface position can be derived from the Dupuit–Ghyben–Herzberg approximation (Bear and Dagan 1964). Accordingly, at point A at the interface, the freshwater pressure equals the seawater pressure:

\[ (h_f + z) \gamma_f = z \gamma_s \]

where \( h_f \) = elevation of the freshwater table above sea level at the vertical location of point A, \( z \) = depth to the saltwater interface below sea level at the vertical location of point A, \( \gamma_f \) = specific weight of freshwater, and \( \gamma_s \) = specific weight of saltwater.

Then

\[ z = \frac{\gamma_d}{\gamma_s - \gamma_d} h_d = G \cdot h_d \]

where \( G \) is the Ghyben–Herzberg factor, which frequently varies between 25 and 30.

However, if the interface is not stationary, the Hubbert hypothesis establishes that the pressure at a given point is the same when the point is approached from both sides, freshwater and seawater. Hence,

\[ (h_f + z) \gamma_f = (h_s + z) \gamma_s \]

where \( h_s \) is the piezometric head of the saltwater above sea level at the vertical location of point A. This can be written in other terms as

\[ S = -z = \frac{\gamma_s}{\gamma_s - \gamma_d} h_d \]

which in terms of \( G \)

\[ h_s = \frac{S + Gh_d}{G + 1} \]

To establish appropriate partial differential equations governing phreatic coastal aquifers, it is necessary to previously define two distinct zones. The continental zone,
Fig 5 Main water contributions to the quaternary alluvial of the Low Guadalquivir River.

Fig 6 Distribution of irrigation, canals, wells and piezometers for calibration.

Fig 7 Comparison between calculated and observed phreatic levels in 5 of the wells and piezometers selected for the calibration of the numerical model.

system is always by flooding. New and old irrigations have different amounts of transits and spatial distributions.

For the purpose of making the appropriate comparisons, we considered first the total recharges coming from precipitation and irrigation (infiltration on the soil surface areas where they exist) as required by the hydrological model SSMA-2 in order to estimate the groundwater recharges on the alluvial aquifer. Secondly, consideration was given to all the freshwater contributions to the surface of the modelled alluvial, that is, precipitation and irrigation. Based on these values, the MELEF model internally calculates the total amount of evapotranspiration, distinguishing between phreatic evaporation and transpiration from the soil, as well as the pertinent groundwater recharges on the free alluvial aquifer.

To carry out the validation of the MELEF evapotranspiration submodel, the groundwater recharges calculated by the SSMA-2 model and the ones obtained using the evapotranspiration submodel were then compared. It is necessary to point out that since the MELEF evapotranspiration submodel considers the actual evapotranspiration as the sum of the phreatic evaporation and the transpiration from the soil, it is possible to separate the two components.

Figure 8 shows the comparison between the recharges calculated using the SSMA-2 model and the recharges simulated by MELEF; however, the latter also takes phreatic evaporation into account. We consider the latter to be the most appropriate comparison, since phreatic evaporation may take place from surface water bodies or even from very shallow phreatic levels under the soil surface.
where only freshwater exists, can be defined whenever $S < P$, that is, where the interface position $(S)$ is below the impenetrable stratum $(P)$, which means that saltwater does not exist. As long as it is possible to find the freshwater/seawater interface $(S > P)$, the coastal zone can be defined by an equation that describes the seawater flow and another equation that describes the freshwater flow. Hence, these equations are as follows:

**Continental zone ($S < P$):**

\[
\begin{align*}
\eta_S &= \frac{K_0 (S - P) \frac{dS}{dz} + K_0 (S - P) \frac{dP}{dz}}{\frac{dS}{dz} + \frac{dP}{dz}} + Q \\
\frac{dS}{dz} &= \frac{K_0 (S - P) \frac{dS}{dz} + K_0 (S - P) \frac{dP}{dz}}{\frac{dS}{dz} + \frac{dP}{dz}} + Q
\end{align*}
\]

where $S$ and $P$ are, respectively, the effective porosities of the freshwater and seawater aquifers accounting for water table and the interface movements.

**Coastal zone ($S > P$):**

\[
\begin{align*}
\eta_S &= \frac{K_0 (S - P) \frac{dS}{dz} + K_0 (S - P) \frac{dP}{dz}}{\frac{dS}{dz} + \frac{dP}{dz}} + Q \\
\frac{dS}{dz} &= \frac{K_0 (S - P) \frac{dS}{dz} + K_0 (S - P) \frac{dP}{dz}}{\frac{dS}{dz} + \frac{dP}{dz}} + Q
\end{align*}
\]

Saltwater:

\[
\begin{align*}
\eta_S &= \frac{K_0 (S - P) \frac{dS}{dz} + K_0 (S - P) \frac{dP}{dz}}{\frac{dS}{dz} + \frac{dP}{dz}} + Q \\
\frac{dS}{dz} &= \frac{K_0 (S - P) \frac{dS}{dz} + K_0 (S - P) \frac{dP}{dz}}{\frac{dS}{dz} + \frac{dP}{dz}} + Q
\end{align*}
\]

Similar equations can be found in the elaboration of other horizontal numerical models with a sharp interface approximation for groundwater flow in coastal aquifers. The numerical model of the simulation of the joint surface-water and groundwater flows also considers the evapotranspiration process from the water surface and soil within the non-saturated zone for every point on the modelled system. The concept of evapotranspiration used in MELEF is illustrated in Fig. 2. The main parameters of the conceptual model are the following: EP (potential evaporation), ETP (potential evapotranspiration), CP (the thickness of the capillary fringe of the soil), TR (total recharge or infiltration at the soil surface) and WT (the water table position referring to the surface of the soil).

As can be seen, the real evapotranspiration (ETR) is calculated as a function of the water table position (WT). This function starts decreasing from the surface of the soil to the thickness of the capillary fringe (CF). This part of the evapotranspiration function is conceptually a phreatic evaporation that cannot be restrained and depends on the values taken by regional potential evaporation from free surface ponding water (EPI, EP2, EPI). The second part of the ETR function, which would have a phreatic level (WT) that is deeper than the thickness of the capillary fringe (CF), corresponds to the transpiration concept and its value must be restrained to the total recharge (TR) at the time of the internal evaluation of the numerical model. This means that when the water table is deeper than the capillary fringe thickness, ETP would never surpass total recharge, that is, infiltration or surface contributions, even if its potential value could be higher. The ETR can go as high as allowed by the total recharge, the ETP and a sufficiently deep water table. In this respect, the position of the phreatic level (WT) is point evaluated by the numerical solution system, and it may be assessed either above or below the surface of the soil.

The utilization of the present conceptual model of real evapotranspiration has a number of important advantages. One of these is that, theoretically, total recharges (mainly precipitation and irrigation doses) can be used with the required spatial and temporal variability. The model could then be used to assess the real evapotranspiration from the calculated phreatic levels during the iterative process of finding the optimal solution of the numerical system.

In keeping with this, it is interesting to note that even though the parameters used in the evapotranspiration submodel have a clear physical meaning, it is highly recommended that verification and calibration be carried out with the aid of actual data from evapotranspiration in the modelled season.

In this sense, the application will consider the analysis of the aquifer recharges as evaluated by the SSMA-2 model (Sacramento Soil Moisture Accounting Model) developed by Sacramento University and modified by the INTECH technical staff (Bumash et al. 1973). This approach will allow the verification of the proposed evapotranspiration submodel as used in MELEF. For this two hydrological years will be simulated so that the recharges furnished by the SSMA-2 model will be used as a basis for comparison with the aquifer recharges simulated by the evapotranspiration submodel of MELEF as calculated from the total recharges of the system, consisting mainly of precipitation and irrigation doses.

The current tool used in water resources modellings, MELEF, is a two-dimensional finite element model for regional groundwater flow through phreatic aquifers developed for a temporal implicit (Eulerian) centered (Crank-Nicholson) and spatially centered (Galerkin) numerical approach. In particular, triangular elements of three nodes allow for the analytical integration of the corresponding numerical formulation to the groundwater flow equations for steady and transient conditions. The pre-processed iterative algorithm GMRES (Saad and Schultz 1986) provides the solution to the system by means of a reduced computer memory and then allows the simple processing of the numerical mesh.

In order to avoid arbitrary assumptions on surface-water and groundwater boundary conditions, a new numerical hydrological concept is proposed. Firstly, all the water resources are considered in the modelled system. Modeling the joint surface-water and groundwater is currently a chief numerical challenge.

The numerical model MELEF uses a simplification of the shallow water governing equations of free surface flows. In particular, as often happens with others commonly used diffusive wave approaches in hydrology, only the classical mass conservation or continuity equation is considered for the present two-dimensional depth averaged model. In this respect, this approach is similar to other methodologies of flood routing along river channels, like it is the case of the Muskingum model developed by G.T. McCarthy in 1934 (Subramanya 1984). Consequently, the range of change of storage in a channel reach can be expressed as

\[
\frac{dS}{dt} = \frac{Q}{x} - \frac{Q}{x} + Q - \frac{Q}{x}
\]

where $S$ is the surface-water storage, $f$ and $Q$ are the inflow and outflow rates in the channel reach, and $x$ is the factor of the Muskingum equation for channel routing.

The equation of continuity, in the vertical direction $z$, of the surface-water thickness, states that the difference between the inflow and outflow rate is equal to the rate of change of storage.

\[
\frac{dS}{dt} = \frac{Q}{x} - \frac{Q}{x} + Q - \frac{Q}{x}
\]

which can be integrated with $m = \frac{1}{x}$ to yield

\[
Q = Q_{	ext{in}} - Q_{	ext{out}}
\]

In this sense, the parameters of water transference are defined as enhanced hydraulic conductivities that behave like transfer parameters adapted to the free surface flow. In particular, the local hydraulic conductivity is then artificially increased by a similar expression:

\[
K'' = K' + mK'\]

where $K''$ and $K'$ are the artificial and real hydraulic conductivities, and $m$ is the saturated thickness of the surface-water, $m$ is the factor used to increase artificially the hydraulic conductivity, which will theoretically depend on the $K''$ factor of the Muskingum equation for channel routing, but in fact can be defined experimentally.

Otherwise, the storage coefficient related to the presence of surface-water would therefore increase to a certain degree, but this would depend on some of the main features such as, for instance, the characteristics of the surface drainage, the numerical refinement of the mesh and the surface-water-groundwater spatial and transient relationships in the context of the numerical resolution parameters. Similar to other techniques of flood routing, the MELEF model requires the fitting or calibration of the parameters in question with the aforementioned numerical simplification of shallow water free surface flow.

In keeping with this and with the aim of obtaining transient numerical solutions of the integrated simulation model, it becomes necessary to smooth out numerically the sharp fronts of properties between the surface-water and groundwater media. On the basis of this numerical requirement, we return to the use of the hydrological concept of the subsol zone (Fig. 3). The subsol zone could be defined as the underlying layer below a riveted, and also below the surface of the soil, which would have intermediate properties of water transference between both media, that is, in the one below, the groundwater per se, and the one above, the surface-water of the soil. This numerical
assumption concerning a subsoil zone with intermediate properties between surfacケースwater and groundwater is the general way MELEF solves numerically interactions between groundwater and surfacケースwater. Anyway, these interactions must be calibrated with field data if available. If riverbed sediments have much lower hydraulic conducケースivity than the underlying aquifer, this must be known and eventually could be considered.

Therefore, the present numerical approach uses the above modelling methodologies of all the water resources of a region in order to consider a two-dimensional coastal aquifer with a sharp interface between the continental freshwater and the saltwater of the sea. The numerical resolution takes place simultaneously for the coastal and the continental modelled sectors.

**Hydrological setting**

The alluvial aquifer from the Quaternary age is part of the Low Guadalhorce River, in southern Spain bordering the Costa del Sol, between the city of Alora and the MediterraneCASEa case in the proximity of Torremolinos and Malaga (Fig. 4).

In some areas this quaternary alluvial rests over a substratum of low to medium permeability from the Pliocene, composed of heterogeneous sequences of clays, marls, sands and conglomerates, and in other areas, over impermeable materials of the Paleozoic substratum belonging to the Alpujarraide complex, within the internal zones of the Betics Cordillera.

Other aquifier materials from the Triassic, mainly marble and limestones, also make up the Alpujarraide complex that outcrops southerly in the Sierra de Mijas. Among the detrital sediments of posterosyn orogenic, a few outcrops of calcareous sandstones of the Miocene are noteworthy, two of which are located in the proximity of Alora and Pizarra. These scarce sediments, which have little aquifer interest, are overlaid by the Pliocene and rest over impermeable materials attributed to the Lower Tertiary. Therefore, it may be concluded that from a hydrogeo- logical point of view, the quaternary alluvial of the Low Guadalhorce River may be considered an unconfined aquifer composed of alluvial fans, palaeochannels, alluvial and colluvial deposits characterized mainly by heterogeneous sequences of clays, sand and gravel or similar unconsolidated detrital materials with moderately high hydraulic properties and thicknesses that range from 8 to 50 m. Then, it can be assumed that the freshwater of the unconfined quaternary alluvial aquifer, that interacts with the surfacケースwater of the Guadalhorce River and the saltwater of the Mediterranean Sea, can be approximCASEly simulated by the present two-dimensional approach of MELEF numerical model.

**Simulation conditions**

In the first place, the simulation of the surfacケースwater and groundwaters has been designed to be adapted to the alluvial valley of the Low Guadalhorce River over the course of four historical hydrological years. The initial condition of the two first hydrological years, 1987/1988 and 1988/1989, is the result of the simulation in a steady state regime that is characteristic of the end of the summer period reached by September, 1987. After all, the simulation of these two first hydrological years allows obtaining likely initial transient solutions from the numerical heating of the initial steady solution. Numerical heating of a model solution during a particular simulation period is strongly recommended to obtain likely initial transient solutions from initially steady ones. The two remaining hydrological years, those that correspond to 1989/1990 and 1990/1991, can then be used in the next phase to calibrate the hydrological parameters of the model developed during this project for the quaternary alluvial.

The correct simulation of the complete transient model, during the 1987/1988-1990/1991 period, has required the time series contributions of surfacケースwaters as measured in the main rivers and simulated in the rest of them) as well as the groundwaters which, coming from neighboring water-sheds, arrive at the discrete numerical model of the Low Guadalhorce alluvial valley. To these freshwater contributions it is necessary to add the lateral groundwater recharges coming from precipitation and from existing irrigation in the sectors adjacent to the modelled alluvial. On the other hand, water recharges are required at the surface of the alluvial itself, which correspond to precipitation and irrigation, as well as of the extractions from pumping carried out throughout the alluvial valley. All the above have contributed to the four hydrological years of simulation, that is, the period of the numerical heating of the model and the calibration period. In this sense, all the time series corresponding to the previous information have been generated for the present project. It was equally necessary for us to have access to all the available information related to the water recharges coming from the cultivated areas of the Sierra of Mijas (Subbasin of Alhaurin el Grande), and from the wastewater corresponding to the return of water usage in the nearby populations, as well as from the river diversions of water through canals with minor irrigation purposes. In this sense, old irrigation is distributed through canals in earth, which can be treated, as the rivers, by filtering canals in the MELEF model because of its integrated approach (Figs. 5, 6).

In addition to establishing the simulation conditions of the transient model regime, a large number of piezometers and wells throughout the alluvial valley were selected. For this purpose the available phreatic levels are used to verify and calibrate the results of the simulations. The calibration of the hydraulic properties of the model has been carried out starting from the evolution of the measured phreatic levels, mainly in the quaternary alluvial, during the simulation period of hydrological years 1989/1990 and 1990/1991. The calibration stage of the surfacケースwater parameters and the main hydraulic parameters of the groundwater flow, hydraulic conductivity and the storage coefficient of the free quaternary aquifer, was carried out in several phases.

**Calibration and validation of the model**

All the above required numerous simulation runs with the transient model until we were able to obtain an acceptable adjustment among the evolution of the water levels, such as, on the one hand, those observed in the different wells and piezometers selected for calibration, and, on the other hand, those calculated by the model at the corresponding numerical nodes.

In any case, the comparisons are shown between the measured and calculated phreatic levels in only 5 (Fig. 6) of the 40 wells and piezometers selected along the whole modelled alluvial of the Low Guadalhorce River (Fig. 7).

The selection of these observation points of the phreatic level followed two general criteria. First, we have considered the relative frequency of recordings during the calibration period. Secondly, it was necessary to give preference to the remote sectors, in the whole alluvial, where information is less sufficient.

Once the calibration of the hydraulic parameters of the alluvial aquifer is carried out, it is necessary to verify or validate the likelihood of the results of groundwater recharge simulated by the submodel of phreatic evaporation and transpiration integrated in MELEF. In order to do this, we used the same period of calibration, i.e., the years 1989/1990 and 1990/1991, since in this case sufficient data on precipitation and agricultural practices of irrigation on the alluvial surface were available.

Therefore, to partially validate the MELEF results during the period in question, the recharges were evaluated as simulated by SSMA-2 from the water distributed through concrete canals. Also, among the latter, a distinction has been made between irrigation by flooding and by leaking. In the case of old irrigation, the
Therefore, SSMA-2 predicts less recharge than MELEF calculated recharge in the modelled system during the winter period, because neither evaporation nor water contributions (precipitation is more important in winter) are accounted by SSMA-2 on free surface waters reasonably. This might even explain, in the case of the MELEF model, the total evapotranspiration values which are higher than the surfacewater contributions themselves, possibly leading to negative groundwater recharges, similar to the concept of discharges from the standpoint of hydrologic balance. In this sense, "calculated exchanges" means also "calculated exchanges" at the water table and at the free surface, and they can overlap the axis labels. Recharges-exchanges can be negative, mainly on summer periods because MELEF model considers firstly the other compounds of the hydrologic cycle, which among others include phreatic evaporation and evapotranspiration.

A preliminary analysis of the results has led us to the conclusion that, for the years 1989/1990 and 1990/1991, the groundwater recharge simulated by the evapotranspiration submodel integrated into MELEF is similar to the groundwater recharge estimated externally by the SSMA-2 model for the different irrigation areas that settle on the soil surface of the Low Guadalhorce alluvial. The main differences are found in the winter and summer periods where the recharges estimated by SSMA-2 are lower and higher, respectively, than the ones simulated by MELEF. These differences may be explained, in the case of the groundwater recharges estimated by the SSMA-2 model, by the failure to consider the phreatic evaporation from surfacewats and riviere areas, which can cause in the winter/summer periods, respectively, an overestimation/underestimation of evapotranspiration, or, in keeping with this, an underestimation/overestimation of the recharges. In this sense, it would therefore be reasonable to consider the recharge simulated by MELEF as more representative of the sector of the free alluvial aquifer of the Low Guadalhorce Valley examined here.

General analysis of results

The validations carried out previously favour the conclusion that the numerical simulations during the period of simulation may be considered, since a 2-year period (1989/1990 and 1990/1991) is involved whereas two years earlier initial transient solutions were obtained by numerical heating (1987/1988 and 1988/1989) after initial conditions were assumed to reach a steady equilibrium by September 1987.

The results of the simulations will be considered likely if sufficient credibility is given to the results of the validation of the conceptual model MELEF for the combined flow of surface and groundwaters, in addition to the validation of the recharges simulated in the quaternary surface of the alluvial valley of the Low Guadalhorce River. Due to space constraints, the results of the transient simulation in the coastal alluvial during the years 1989/1990 and 1990/1991 are only presented for two specific times (Figs. 9, 10, December 30, 1989 (after a period of extreme flooding) and September 30, 1991 (during a period of severe low water).

It is important, nevertheless, that the results obtained in the sector near the coast should be considered approximate, in terms of the phreatic levels (Parameter 5 which is near the coast) as well as the thicknesses of the saltwater from the sea. The main reason, although not the only one, may be attributed to the lack of data in this sector on lateral recharges coming from losses in the water supply and, mainly, the sanitary network of the city of Malaga and bordering populations. Moreover, no data are available that allow the calibration of the movements of the seawater.
interface in the sector nearest to the coast, which means that this assessment of the evolution of the saltwater-freshwater interface is not as yet conclusive.

Conclusions

The present work was carried out using a numerical modelling approach for the joint flow of groundwater and superficial water along the coastal alluvial valley of the Low Guadalhorce River. This simulation was performed on water contributions and usages which are characteristic of four hydrological years: 1987/1988 and 1990/1991. The model used, MELEF, was calibrated for a simulation period prior to the channeling of the river and corresponding to the years 1989/1990 and 1990/1991. As reference elements for the validation of the model, the phreatic levels used were measured in a large number of wells and piezometers, and the groundwater recharges were obtained by the hydrological model SSMA-2 from the precipitation and surface irrigation of the alluvial valley in order to validate the groundwater recharges calculated by the MELEF model. In this respect, we consider the results obtained during the calibration and validation periods are quite accurate.

In keeping with this, the current modelling of the alluvial valley has allowed us to determine the evolution of the water levels, both the groundwater in the quaternary alluvial aquifer, as well as the surfacerwater and its depth in the flow network of active drainage, during the entire simulation period 1987–1991. Also the simulation of transient flow behaviour has made it possible to study the evolution of the saltwater-freshwater interface as a solution to the state of the freshwater discharge of the coastal sector of the aquifer towards the Mediterranean Sea.

The joint modelling of the groundwater and surface-water by means of the MELEF model provides knowledge in real time of the water resources and existing water storage in the aquifer. It is also possible to predict the appearance and disappearance of surfacerwater in the rivers as a result of water interactions between the river and the aquifer, as related to nearby freshwater usages (wells for agricultural irrigation, supplies, water diversions, etc.) and to losses owing to evapotranspiration. Moreover, the current used modelling facilitates the treatment of extreme hydrological events, as well as the evaluation of their consequences, such as floods of short and medium length. This type of transient modelling provides information on the movement of the freshwater-saltwater interface that is characteristic of the coastal aquifers under study. Hence, in the case of freshwater overexploitation, it is also possible to predict the contamination of freshwater pumping wells near the coast with saltwater from the sea.

In our opinion, all the above can serve as a valuable tool to study the best options for future freshwaters exploitation and the defence and management of water in the alluvial coastal valley of the Low Guadalhorce River.

Acknowledgements

This research is sponsored by the Ministerio del Medio Ambiente as part of a project supported through Intecas. The work has been performed in a joint effort with the Intecas-institute trust and Confederacion Hidrografica del Sur.

References

DHI (1997) MIKE BASIN. A tool river planning and management. Horshelm, Danish Hydro. Inst., Denmark