Hydrodynamic characteristics of the western Doñana Region (area of El Abalario), Huelva, Spain

Thomas Trick · Emilio Custodio

Abstract The Doñana region, in southwestern Spain, comprises a large and important nature reserve, the wetlands of which are affected by human activity. Planting of an extensive eucalyptus forest in the 1950s and, more recently, the use of aquifers for irrigation and water supply for some coastal tourist resorts, have altered the natural groundwater-flow system. The area of the study is the western sector of the region, called El Abalario, which is a gentle topographic elevation between the Atlantic coast and La Rocina Creek (Arroyo de la Rocina). Underneath a variable layer of eolian sands with high dunes near the coast, thick Plio-Quaternary detritic strata, mostly fine silica sands, overlie marls. Near the base there is a variable, deltaic-origin layer of coarse sands and gravels. The dome-shaped water table, inside the sands, is close to the surface everywhere except beneath the dune belt, and small, temporary, shallow lagoons are numerous. The coarse sand and gravel layer conditions groundwater flow and behaves as a semiconfined layer between sands. A cross section through the area was simulated with a model to check the validity of the conceptual groundwater-flow pattern and its sensitivity to the hydraulic parameters. The model was calibrated using parameter values obtained by pumping tests and multilevel piezometric data, and checked against the estimated groundwater discharge into La Rocina Creek. Groundwater flows peripherally to the sea coast, to La Rocina Creek, or directly east and southeastward into the Doñana marshlands, in the Guadalquivir River delta. The average net aquifer recharge rate was calculated to be between 100 and 200 mm year^{-1} for the area covered by brush, but is remarkably lower in the areas of eucalyptus trees. The transient-state model shows that recharge varies spatially and is not clearly proportional to annual precipitation. Phreatic evapotranspiration plays an important role in decreasing the net value of aquifer recharge to approximately 0.4–0.6 of that calculated with a soil-balance model. The cross section model was used to study the effect of groundwater abstraction on water-table depth by subtracting the contribution of vertical flow, calculated by a well-hydraulics formula, to the semiconfined deep aquifer. The result was a decrease in phreatic evapotranspiration, flow into La Rocina Creek, and lagoon-inundation frequency. Replacement of the eucalyptus forest with native vegetation may raise water-table levels and even reactivate old tributaries to La Rocina Creek.

Résumé La région de Doñana, située dans le sud ouest de l'Espagne, comprend une importante réserve naturelle avec des zones humides, affectée par l'activité humaine. L'exploitation de vastes plantations d'eucalyptus pendant les années 50 et l'usage plus récent des nappes souterraines pour l'irrigation et l'alimentation en eau des centres touristiques côtiers ont modifié le système de flux d'eau souterraine dans cette zone. La présente étude a été réalisée dans le secteur occidental, appelé El Abalario. Ce secteur consiste en une légère élévation située entre l'Océan Atlantique et la ravine de La Rocina. Une couverture variable de sables éoliens, formant une haute crête dunaire côtière, recouvre des sédiments detritiques plio-quaternaires, déposés eux même sur des sables siliceux lesquels reposent à leur tour sur des marnes. Près de la base se trouvent des sables grossiers et des graviers d'origine deltaïque, dont l'épaisseur varie spatialement. Le flux d'eau souterraine est conditionné par l'aquifère semi confinés des graviers et des sables grossiers. Le niveau phréatique de l'aquifère libre des sables fluvio-marins est peu profond, excepté sous les dunes. On y trouve souvent des petites lagunes temporaires peu profondes. Le flux de l'eau souterraine a été simulé dans une section verticale pour vérifier le modèle hydrogéologique conceptuel et la sensibilité aux variations des paramètres. Le modèle a été calé en utilisant d'une part les valeurs des paramètres hydrauliques obtenus par des essais de pompage et d'après les données piezométriques mesurées à différentes profondeurs, et d'autre part l'apport estimé de la ravine de La Rocina.

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L'écoulement d'eau souterraine s'effectue par drainage latérale dans trois directions, d'une part vers la côte, d'autre part à travers la ravine de La Rocina et finalement directement vers les Marais de Doñana situés à l'est et sud-est dans le delta du fleuve Guadalquivir. Avec une pluviométrie moyenne comprise entre 550 et 600 mm, la recharge nette moyenne annuelle des nappes, pour des périodes de temps assez longues, est estimée entre 100 et 200 mm dans les aires de végétation autochtone, et elle est nettement inférieure dans les aires plantées d'eucalyptus. Le modèle transitoire montre que la recharge varie dans l'espace et qu'elle n'est pas clairement proportionnelle aux précipitations annuelles. L'évapotranspiration phréatique joue un rôle important et diminue la valeur nette de la recharge des nappes de 0,4 à 0,6 de la valeur calculée avec un modèle de bilan d'eau dans le sol. La section modélisée est utilisée pour étudier l'effet de l'extraction d'eau souterraine sur la profondeur du niveau phréatique en soustrayant le flux vertical, calculé grâce à une formule d'hydraulique des puits, de la nappe profonde semi-confinée. Le résultat de cette extraction est une diminution de l'évapotranspiration phréatique, du flux au niveau de la ravine de La Rocina et de la fréquence d'inondation des lagunes. La substitution de forêts d'eucalyptus par de la végétation autochtone peut permettre la remonté des niveaux phréatiques et même réactiver d'anciens ravins affluents à La Rocina.

Resumen La región de Doñana, situada en el sudoeste de España, incluye una gran e importante reserva natural, cuyos humedales están siendo afectados por la actividad humana. La extensa plantación de eucaliptus en la década de 1950 y el uso más reciente de los acuíferos para riego y para abastecimiento de centros turísticos costeros han modificado el sistema de flujo del agua subterránea en esta zona. Este estudio se ha realizado en el sector occidental, llamado El Abalario. Se trata de una elevación suave situada entre el océano Atlántico y el arroyo de La Rocina. Debajo de un manto variable de arenas eólicas, que forma un alto cordón dunar costero, se encuentran sedimentos detríticos plio-cuaternarios formados por arenas silíceas finas, que hacia la base incluyen una capa de arenas gruesas y gravas de origen deltrico, los que a su vez yacen sobre margas. El flujo de agua subterránea está relacionado con niveles de gravas y gravillas semiconfinadas por las arenas fluvio-marinas que contienen el nivel freático. El nivel freático es somero excepto debajo del cordón dunar. Son frecuentes pequeñas lagunas temporales. Se ha simulado el flujo de agua subterránea en una sección para comprobar el modelo de flujo conceptual y la sensibilidad a variaciones de los parámetros. El modelo fue calibrado usando los valores de los parámetros hidráulicos obtenidos en ensayos de bombeo y datos piezométricos medidos a diferentes profundidades, y la descarga estimada al arroyo de La Rocina. La recarga de agua subterránea drena lateralmente, por un lado hacia la costa y por otro lado a través del arroyo de La Rocina, o directamente hacia las Marismas de Doñana situadas en el delta del río Guadalquivir. Con una lluvia media anual entre 550 y 600 mm, la recarga neta media estacionaria anual del acuífero, considerando periodos de tiempo largos, se estima entre 100 y 200 mm en las zonas de vegetación autóctona, y es notablemente menor en las zonas de plantación de eucaliptos. El modelo transitorio indica que la recarga varia espacialmente y no es claramente proporcional a la precipitación para periodos de un año. La evapotranspiración freática varia espacialmente y juega un papel importante; disminuye el valor neto de la recarga al acuífero para dejarlo en 0,4 a 0,6 de lo que se calcula mediante un balance de agua en el suelo. La sección modelada sirve para estudiar el efecto de la extracción de agua subterránea sobre la profundidad del nivel freático mediante la substracción del flujo vertical, que se calcula mediante una fórmula de hidráulica de pozos para el acuífero semiconfinado profundo. El resultado es una disminución de la evapotranspiración freática, del flujo al arroyo de la Rocina y de la frecuencia de inundación de las lagunas. La substitución del bosque de eucaliptus por vegetación nativa puede elevar los niveles freáticos e incluso reactivar antiguos "caños" tributarios al arroyo de La Rocina.

Keywords Water table · Lagoons · Wetlands · Effects of groundwater exploitation · Cross-sectional model

Introduction

The Doñana area, as shown in Fig. 1, is located in southwest Spain. It is bounded to the east and south by the Guadalquivir River and the Atlantic Ocean, respectively, and extends to the west up to the Rio Tinto River marshlands. The area includes extensive wetlands (200 km^2 of the 1,400 km^2 of primitive marshland), a large number of small, temporary lagoons, and peripheral areas of brush and forest which are scarcely inhabited. These areas make up one of the largest and richest wildlife reserves and settling areas for migrating waterfowl in Europe. Part of the area is now a National Park, created in 1969, and surrounded by a Natural Park. There are also intensive agricultural areas, developed mostly in the 1980s, and some large tourist resorts developed since the 1970s along the coast (Matalascañas and Mazagón) and the villages of El Rocío and Almonte. Groundwater is pumped for irrigation and water supply, and is extracted by an extensive eucalyptus forest around the marshes, which was planted around the 1950s and 1960s (García-Murillo and Sousa 1999). To some extent this is reducing the water available for the seasonal marshland and shallow lagoons, especially during the dry summers. Significant direct groundwater exploitation did not start until the early 1970s, and particularly in the 1980s, when the approximately 10,000 ha groundwater irrigation project "Almonte–Marismas", was put into operation in an area surrounding the Doñana National Park. More than 400 wells were drilled at this time, providing much unprecedented knowledge of the aquifers in some areas, and a large number of pumping tests were performed

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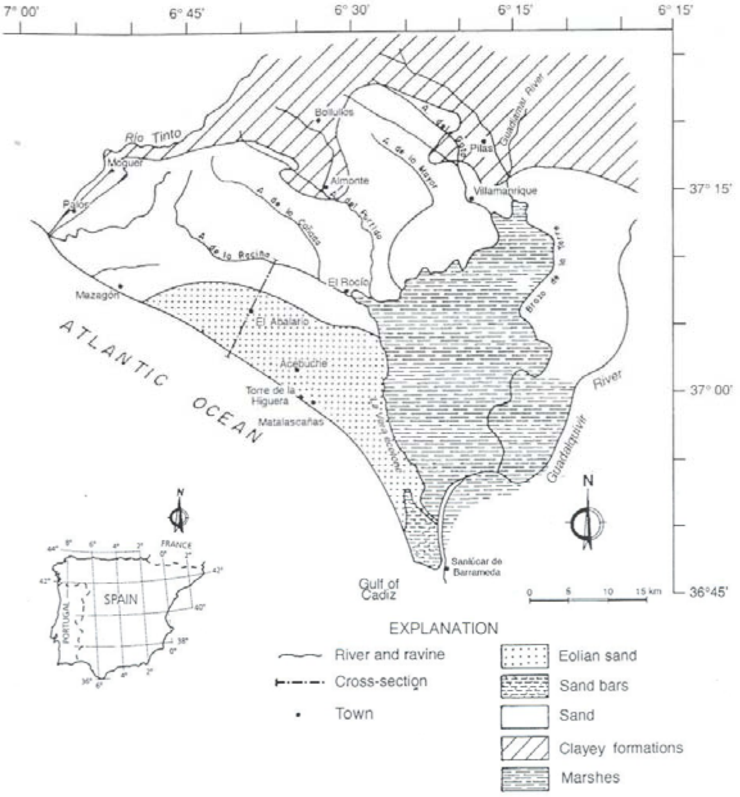

Fig. 1 Map of El Abalario area showing surface features and lithology of shallow strata. Sand means undifferentiated types of sand (e.g., fluvio-marine). "A." means arroyo or creek; "Brazo" means "branch". The La Vera is the contact strip (ecotone) between the sands and the marches

within the irrigation area by different national organizations (Instituto Andaluz de Reforma Agraria, IARA; Instituto de Reforma y Desarrollo Agrario, IRYDA).

Groundwater abstraction for irrigation amounts to 45–60 hm^3 $year^{-1}$ (cubic hectometers or million m^3 per year), and the tourist resorts abstracts an additional 3–4 hm^3 $year^{-1}$, with sharp peaks of demand during the summer season and especially on weekends. Outside these areas, hydrogeological data were very limited until the early 1990s, except for some wells supplying a few, now abandoned villages, and a water-level monitoring network operated by the Geological Survey of Spain (IGME), using available shallow wells and boreholes. Inside the irrigation area, the groundwater monitoring network is much denser.

In the El Abalario area there are five main localities (shown in Figs. 1 and 2) where groundwater is intensively abstracted, mostly by means of deep wells:

1. The Almonte–Marismas irrigation sectors IV and III, around El Rocío, which include some supply wells. Total groundwater abstraction is about 16 hm^3 $year^{-1}$. Locally, a persistent downward trend in the deep-aquifer piezometric levels of about 0.5 m $year^{-1}$ has been observed (from 1980 to 1995), but currently (2000) this is now leveling off, partly due to a groundwater abstraction reduction.
2. The tourist resort of Matalascañas. Groundwater abstraction is between about 2.5 and 3 hm^3 $year^{-1}$ from six main supply wells.
3. The tourist resort of Mazagón uses about 1 hm^3 $year^{-1}$ of groundwater from three deep wells.
4. The intensive irrigation area around Moguer, near the lower reaches of the Río Tinto River. Groundwater abstraction is distributed over a large area and amounts to several cubic hectometers per year.
5. The visitors' area of El Acebuche, in Doñana National Park. Groundwater abstraction is normally less than 0.5 hm^3 $year^{-1}$, mostly to maintain an artificial lagoon area and supply water to some facilities.

In the late 1980s and early 1990s, to supplement previously limited information in some areas, the Public Works Geological Service (SGOP) and the Guadalquivir Basin Water Authority (CHG) drilled and installed a new network of piezometers screened at different depths, under the design and guidance of the Department of Geotechnical Engineering (DIT) at the Technical Univer-

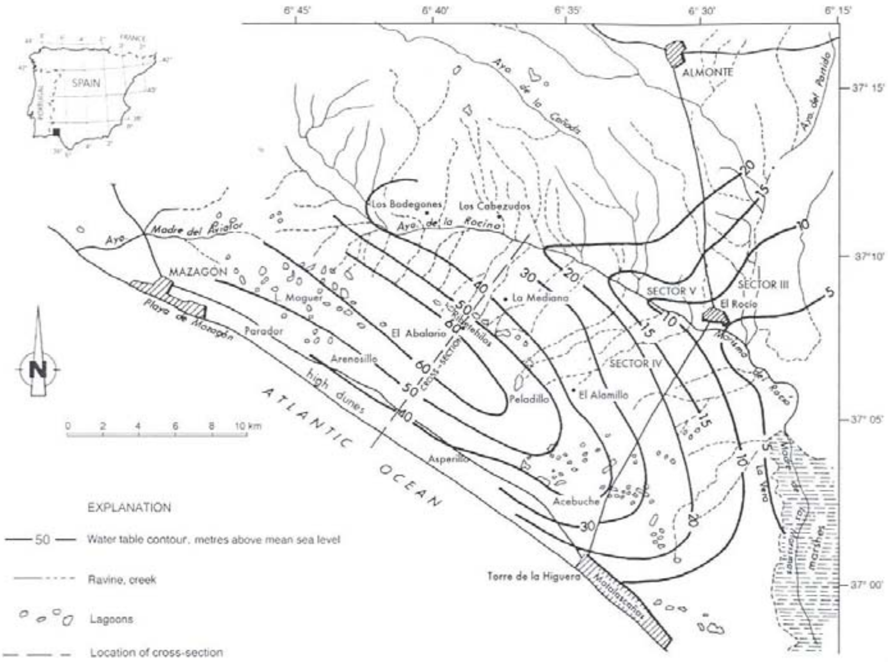

Fig. 2 Water-table map of El Abalario area (modified and corrected after Custodio and Palancar 1995). "Ayo" means arroyo or creek

sity of Catalonia (Custodio and Palancar 1995; Mantecón et al. 1995). This network has now been extended and completed by the Geological Survey of Spain (IGME, ITGE) with the cooperation of the DIT. Additional data needed on the hydrology and geology of the coastal area can now be acquired.

During the 1990s the eucalyptus plantations in the parks were eradicated in order to restore natural brush vegetation (white scrub) where the water table is relatively deep (2–3 m), underneath the old, partly flattened dunes, or phreatophyte woodland (black scrub) where the water table is shallow. This has had a major impact on the groundwater balance, at least locally. The change from the former situation to the new one extends over several years.

This paper presents the main hydrodynamic characteristics of the area, which is one of the main recharge areas of the Doñana region aquifers, the modeling selection of a representative cross section, first under steady-state conditions to investigate the validity of the conceptual hydrogeological model, and then under transient conditions to obtain spatial and temporal changes of recharge. The results form the basis for evaluating the effect of groundwater abstraction on vegetation cover and groundwater discharge, and the effects of vegetation management in large areas.

General Description of the Study Area

The El Abalario study area is located in the western part of the Doñana region and covers about 360 km^2 (Fig. 2). The water-table surface is smooth, dome-shaped, and attains a height of 60 m above sea level. The coastal dunes, over 100 m high, end abruptly in a coastal cliff, that is retreating due to sea abrasion. To the west and east the land elevation decreases towards the Rio Tinto River and Guadalquivir marshes, respectively. The climate is semihumid Mediterranean, with some influence from the Atlantic Ocean. The average rainfall is about 550–600 mm year^{-1}. More than 40% of the rain falls during the winter, and about 25% during the spring and also during the autumn. Yearly rainfall varies between less than 350 mm and more than 1,200 mm, with distinct dry and wet inter-annual sequences. In broad terms, rainfall decreases from west to east and inland from the coast. Storms can be very irregularly distributed, with different impacts from one area to another. The summer is remarkably dry. The average annual temperature ranges between 16 and 17 °C.

Groundwater is practically the only source of freshwater. Economic development of the western Doñana region depends largely on the aquifers and their sustainable use. The El Abalario area is an important groundwater recharge zone. From previous hydrogeological models and water-balance data, based on old and limited

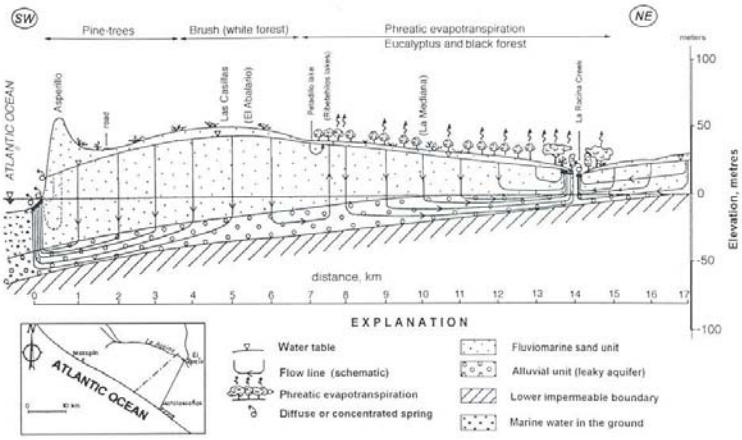

Fig. 3 Schematic groundwater-flow pattern in a north–south cross section through El Abalario, assuming that sand vertical permeability is much lower than deep aquifer horizontal permeability. Minor lateral flow through the fluvio-marine sand unit was reported by Custodio and Palancar (1995)

databases, very different and uncertain average recharge values were obtained, from as low as 40 mm year^{-1} to more than 200 mm year^{-1}. In a very wet year, recharge in bare dune sand can be as high as 500 mm. A series of studies was carried out to estimate recharge more accurately by means of hydrodynamic and chemical methods, and soil-water balance, and soil-water transport methods (Iglesias et al. 1996; Trick and Custodio 1997; Iglesias 1999; López-Rodríguez and Giráldez 1999; de Haro et al. 2000). The studies here were carried out to improve knowledge of the groundwater balance of the El Abalario area and to evaluate the impact of groundwater abstraction on vegetation and wetlands by means of simple but detailed hydrodynamic modeling, taking into account aquifer layering and groundwater head potentials at different depths (Trick 1998). The boreholes, monitoring network, and other studies carried out since the mid-1980s have contributed valuable data to this study.

Hydrogeological Characteristics

The most recent contributions to the geology of the region have been made by Salvany and Custodio (1995), Borja and Díaz del Olmo (1996), Rodríguez-Ramírez (1996), Zazo et al. (1996), Dabrio et al. (1999), and Rodriguez et al. (2000). Continental-shelf geology was studied by Maldonado et al. (1999). Recently, after the huge tailings basin of the Aznalcollar sulfide mine broke down, in the middle area of the Guadiamar River, which flooded the Guadiamar valley at the eastern edge of the Doñana area and the marshes, major new geological and hydrogeological studies have been contributed (IGME 2001), mostly to the north and east of the area under consideration. An International Commission of Experts (ICE 1992) prepared a critical review of the factors affecting the development of the region, including a discussion of existing groundwater-flow models and a detailed discussion of hydrogeological uncertainties. The impact of human activity on groundwater resources is described in Llamas (1990), Suso and Llamas (1993), Custodio (1994, 1995, 2000),and Custodio et al. (1994).

Analysis of all existing piezometric data, as well as the data obtained during drilling of new boreholes for the groundwater monitoring network, were used to define an improved hydrogeological conceptual model on which to base hydrodynamic modeling. The relatively thick sand deposits, occasionally inter-layered with finer sedimentary materials, form a relatively low permeability, unconfined upper aquifer directly overlying a heterogeneous lower aquifer which behaves hydraulically like a semi-confined one below the fine sands, whose role approaches that of an aquitard. The hydraulic transmissivity of the lower and thinner aquifer is higher than that of the upper aquifer, due to the inclusion of coarse sand and gravel-containing layers. The lower boundary of this two-layer aquifer system, which is of Plio-Quaternary age, is formed by the clayey sands of the transition to Miocene marls at the bottom of the lower aquifer. In the following discussion, k, k′, T, and S will indicate, respectively, horizontal and vertical permeability of the aquifer, transmissivity, and storage coefficient, and subscripts 1 and 2 refer, respectively, to the upper fine sand aquifer and to the deep coarse and gravely aquifer.

In Fig. 3 a generalized flow net in a southwest–northeast cross section follows the groundwater flow lines. It shows that part of the rainwater that recharges the low permeability (k_1) upper aquifer tends to flow mostly vertically toward the lower aquifer, where flow lines are mostly horizontal (Fig. 3). Groundwater flows to the south and discharges into the Atlantic Ocean, and to the north into La Rocina Creek, which is the main permanent tributary to the Guadalquivir marshlands. The shape of the water table closely matches the land surface, except for the local relief of the sand dunes. In the eucalyptus tree area, before this was eradicated, root uptake occurred directly from the water table through the capillary fringe (phreatic evapotranspiration).

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Figure 3 shows the thickness of the two permeable formations along the cross section. The values represent a strip several kilometers wide, but they change from west to east (Salvany and Custodio 1995).

The area has a large number of small, temporary lagoons (Borja and Díaz del Olmo 1987; Sousa and Garcia Murillo 1999), which respond to different hydrological conditions. During shallow water-table stages, groundwater fills a series of seasonal lagoons. Other lagoons depend mainly on rainfall, although in the past some of them were also manifestations of the water table before it was permanently lowered by nearby groundwater abstraction.

Steady-State Cross Section Modeling

The conceptual hydrogeological model was checked by means of a two-dimensional vertical cross-section, finite-difference, groundwater-flow model, considering two hydrogeological layers. The upper layer represented the thick fine-sand aquifer and the lower one the thinner, coarse-grained aquifer. La Rocina Creek, at the northern model boundary, is a main groundwater outflow zone, which is simulated as a drain since the water table in this tract is always above the creek elevation. At the southern edge of the model the ocean was simulated as a constant-head boundary corresponding to mean sea level.

The penetration of the fresh-water–salt-water interface was estimated applying the Badon Ghijben–Herzberg method for steady-state conditions, and the length of the fresh water discharge face was estimated using Glover's equation (Custodio and Llamas 1983). Using the estimated hydraulic-parameter values obtained by hydraulic testing, the aquifer geometry, and a reasonable steady-state recharge range between 100 and 200 mm year^{-1}, calculations show a steep fresh-water–salt-water interface, which means close-to-vertical fresh-water flow. Accordingly, the fresh-water–salt-water interface was assumed to be a nearly vertical, steady-state no-flow boundary, which is assumed a reasonable simplification (Custodio 1992), even considering the vertical changes of groundwater head.

Within the area of eucalyptus and black scrub forest, water uptake by the trees from the saturated zone starts when the simulated water table attains a certain threshold height. To calculate direct evapotranspiration from the water table, the MODFLOW computer code utilized (McDonald and Harbaugh 1988) has two parameters: maximum evaporation rate and extinction depth. Field values of these parameters were not available and are difficult to obtain, so these had to be adjusted with the flow model within a plausible range of values. Starting guideline values were, respectively, 500–800 mm year^{-1} for the maximum evaporation rate, and an extinction depth between 3 and 5 m for the eucalyptus trees, and between 2 and 3 m for native black scrub and pine trees. The calibrated phreatic evaporation rate was 350–700 mm year^{-1}, which is higher than local recharge and even rainfall in dry years, in which the model suggests a consumption of groundwater reserves.

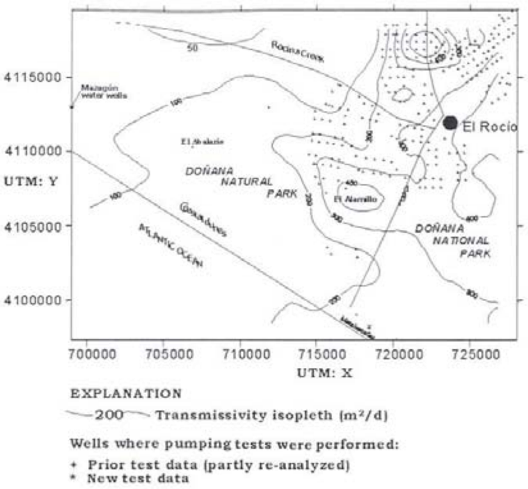

Fig. 4 Distribution of deep-aquifer transmissivity values. + indicates wells with data from pumping test carried out in former studies. * indicates wells and monitoring boreholes in which additional pumping tests have been carried out for this study. *X* and *Y* are the coordinates in meters referred to the Universal Transverse Mercator (UTM) projection

Formerly information on the units' hydraulic properties was obtained through pumping tests, which were conducted from 1993–1996 using the new observation piezometers and some older water-supply wells (Trick and Custodio 1996). Results from preliminary estimates were checked using an automated calibration method (Carbonell 1989). Figure 4 shows the spatial distribution of deep-aquifer transmissivity (T_2), which varies from 70 m^2 day^{-1} at Mazagón to more than 400 m^2 day^{-1}. Corresponding permeability values vary from 4–6 m day^{-1} in the west to about 9 m day^{-1} in the northeast.

In order to analyze the vertical head gradients and to take into account the suspected existence of low permeability layers inter-bedded with the sands, mostly clayey seams and peat layers which are sometimes not clearly recognized in the boreholes but are clearly seen in the sea cliff, a vertical four-layer numerical groundwater flow model shown in Fig. 5 was constructed in a first stage, using the code MODFLOW (McDonald and Harbaugh 1988).

As shown in Fig. 6, the four-layer model confirms the conceptual flow model, although the flow pattern is less clearly divided into vertical and horizontal flow lines. It is estimated that the deep aquifer transmits about 80% of the recharge laterally.

The steady-state cross-sectional groundwater-flow model was calibrated using data from points close to the cross section. They are relatively scarce and various tests have been conducted to fill data gaps. They consist

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of determining hydraulic parameters values obtained through pumping tests and piezometric field data. Results have been checked against the evaluated average discharge to the La Rocina Creek. No direct data on creek flow was available when the model was calibrated, except for a short period, although there were some additional qualitative appreciations. Even now, when the groundwater discharge to Rocina Creek can be calculated from the flow rates measured at the gauging station situated at the mouth of La Rocina Creek, close to the village of El Rocío, they must be corrected for the groundwater discharge downstream and the significant water loss due to the high evaporation rate along the creek, especially in summer and in some wide-channel tracts in which the river ponds. As shown in Fig. 7, the hydraulic heads at different depths, obtained from the piezometer network installed during the 1990s, remarkably improved the estimate of the steady-state recharge rate (R) calibrated with the flow model.

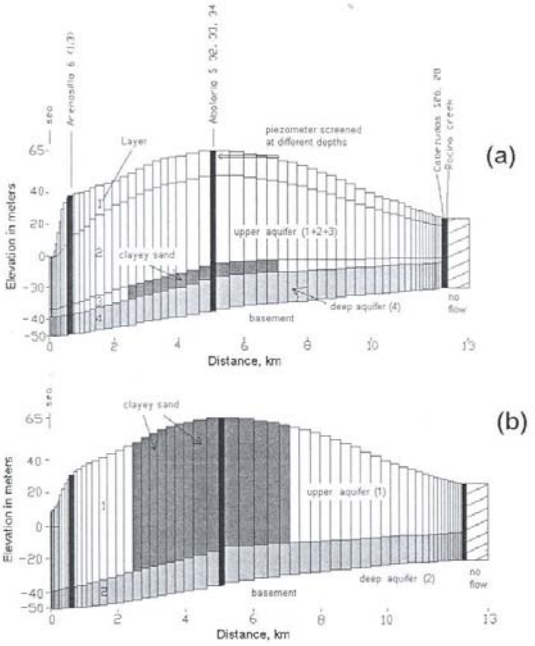


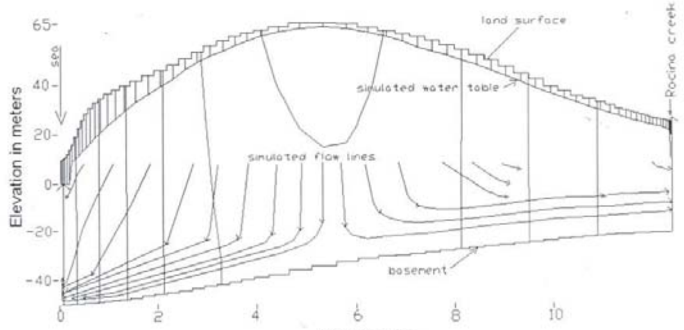
Fig. 5 Four- and two-layer discretization ("*a*" and "*b*", respectively) of the simulated cross-section, showing the different characteristics of the layers and the boundary conditions. The bottom (basement) and sides are assumed no-flow boundaries and the top is the water table with imposed recharge. The *black columns* indicate multilevel piezometers used for the calibration. In the four-layer discretization the *shaded parts* indicate a vertical permeability decrease of the sands. In the two-layer discretization (*b*) the deep aquifer is *dark-shaded* and the *light-shaded columns* (layer 1) represent reduced permeability (more intense towards the centre) to simulate the effect of the third layer of the four-layer model in the centre and at the sea boundary

The results of the four-layer model indicate that the upper aquifer can be simulated with a single layer, without losing much accuracy. This simplification is valid for this model scale. However, model discretization may be inappropriate to get detailed results in particular areas. The main difference between the four and two-layer model discretizations (Fig. 5) is the simplification of the groundwater discharge into the sea at the coastal model boundary. The deep layer is linked to the sea by means of a hydraulic resistance, which is a parameter without a precise physical meaning, to be calibrated considering the results obtained with the four-layer model. A second major required modification was the calibration of an equivalent anisotropic permeability of the upper model layer, which was a consequence of combining layers of different permeability into one layer. The two-layer model was found suitable to represent the functioning of the system and was applied to make it easier to simulate a long transient period with many time steps.

Results of the Steady-State Simulation

The results of this groundwater-flow model back up the conceptual model of a relatively thick, unconfined, fine-sand aquifer overlying a lower and more permeable aquifer where most of the lateral flow toward the discharge zones is concentrated. In practice it is like a

Fig. 6 Simulated flow lines in the vertical cross section of the four-layer discretization. Upward flow at the sea and at La Rocina Creek is not shown since it occurs in a short horizontal distance



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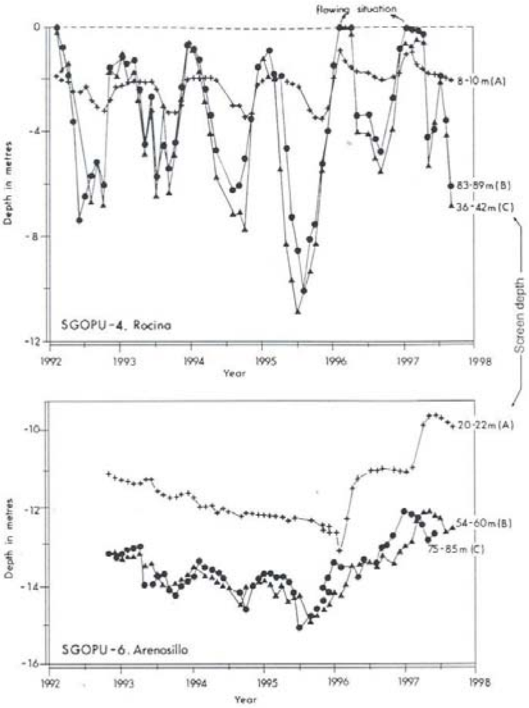

Fig. 7 Hydraulic-head data from two multilevel monitoring boreholes in the El Abalario area. SGOPU–4 [contains piezometer tubes (A), (B), and (C)] is close to the mouth of La Rocina Creek, where the channel is at about 2.5 m lower. Tubes (B) and (C) show the influence at that time of seasonal agricultural abstractions (this borehole is near the irrigated area). SGOPU–6 [contains piezometer tubes (A), (B), and (C)] is close to the cross section, near the coast, but on the inner side of the littoral dune belt. There is a large downward vertical head gradient since this is a recharge area, besides the influence of the seasonal abstractions at Mazagón from the deep aquifer

semiconfined aquifer below a thick aquitard. With the exception of the high dunes, which are smaller than the spatial resolution of the model, it produced simulated piezometric heads which differed from observation more than the error criterion (as will be discussed later) only within a small strip near the coast. This was due to the difficulty of accurately modeling the groundwater-seepage face along the coastal cliff and the high groundwater-head gradients, without unnecessarily increasing the complexity of the model. A simple model was enough to meet the objectives of the study.

An average upper aquifer permeability (k_1), of about 0.1 m day^{-1}, was adjusted from the steady-state flow model. Actual permeability values may differ one order of magnitude from this value, due to the lithological heterogeneity of the sand formation, which contains layers of less permeable material. Hydraulic tests in boreholes gave values in the range 0.01–0.1 m day^{-1}, but in some areas the range of 0.1–1 m day^{-1} was more appropriate. Laboratory measurements were unreliable because of washing out of fine material in the sand samples, and poor compaction. Transmissivity of the lower confined aquifer (T_2) showed a clear horizontal variation, due to some heterogeneity and increasing thickness of this layer towards the north and the east. T_2 ranged from about 70 m^2 day^{-1} in the northwestern part to more than 400 m^2 day^{-1} north of El Rocío. In the centre of the piezometric dome, close to the abandoned village of El Abalario, there was a relatively large vertical hydraulic-head difference of about 5 m, between the water table in the upper aquifer and the piezometric level in lower aquifer as measured in point piezometers screened at various depths along a vertical distance of 60 m. This head difference is caused by the occurrence of clay layers inside the sands of the upper aquifer, which seem more abundant in a strip which behaves as a relatively low vertical-permeability zone. The ratio between bulk vertical permeability (k'_1) and bulk horizontal permeability (k_1) was adjusted to approximately 1/50 in this strip.

The calibrated steady-state recharge ranged between 100 and 200 mm $year^{-1}$. However, this value was remarkably lower in areas of eucalyptus trees, due to the fact that phreatic evapotranspiration had to be subtracted to obtain net recharge. Under these conditions, the amount of groundwater removed could be higher than rainfall and negative net recharge is locally possible. This has been álso measured elsewhere (Calder et al 1997).

The sensitivity analysis shows that: (1) the simulated position of the water table was sensitive to changes in recharge (R) and to the transmissivity of the lower aquifer, T_2; (2) the piezometric head difference between the upper and lower aquifer is sensitive to changes in R and to aquifer anisotropy ratio, k'_1/k_1; and (3) the discharge to La Rocina Creek is sensitive to changes in R and to the maximum evaporation rate. A variation in the k_1 values within the range of values resulting from the pumping tests in boreholes does not significantly affect the model results.

Under the circumstances used for calibrating the cross-sectional model, when the planted eucalyptus forest existed, about 40% of total recharge in the study area discharges into the ocean, between 11 and 20% into La Rocina Creek, and over 40% is phreatic evapotranspiration through the eucalyptus trees. This means that groundwater uptake of this forest is higher than total abstraction of the large irrigation area located in the northeastern sector of the study area.

Transient Cross Section Modeling

To obtain the recharge function (RF) to be used as an input function for the transient groundwater-flow model, a code was used for daily soil-water balance (Samper et al. 1999, using the software version of 1992, BALAN 8.0). The code includes functions to consider the maximum rate of rain infiltration and the eventual possibility

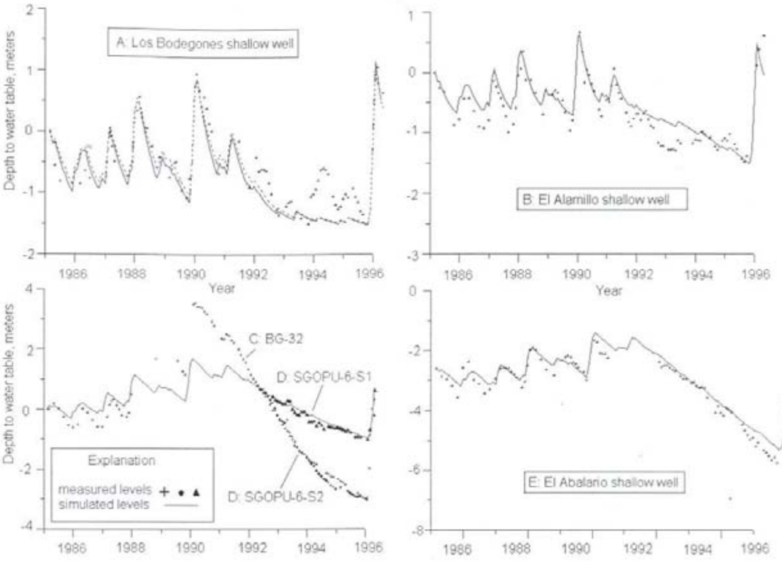

Fig. 8 Comparison of simulated water-table depths with records from the ITGE/IGME). The period comprises a normal, a wet, and a dry period

of transitory saturation within the unsaturated zone. Calculated recharge is converted to the equivalent water-table increase, which is added to a single-cell exponential water-table depletion function, depending on a lumped depletion factor which is to be calibrated. This allows for some recharge calibration, either manual or automatic, although the single-cell model may be too coarse for actual conditions.

A preliminary calibration of calculated recharge was performed by fitting a simulated water table with measured head values in shallow wells and piezometers. Thus, a historical series of 18 years of monthly recharge values was produced, including wet, normal, and dry periods. However, the calculated RF is considered as a rough estimate because the model uses a series of parameters (Samper 1997; Samper et al. 1999), some of which are very difficult to measure or estimate, such as drainage constants or concentrated recharge fractions. They are therefore estimated through the calibration process, as well as the approximate approach of the single-cell groundwater-level response function. Since the phreatic evapotranspiration was not considered, the RF is greater or equal to net recharge to the water-table aquifer. RF is consequently only a starting function whose shape can be used as a guide for transient simulation but which has to be non-linearly scaled, taking into account seasonal response.

Field surveys have shown that after a dry period the sandy top soil develops water repellence. This means that when rainfall starts, water drops move on the soil surface and concentrate in the numerous small depressions of the sand microtopography. There the concentrated rainfall infiltrates and for sufficiently large events part of this water has a better chance of becoming recharge. This fact cannot be reasonably simulated by the recharge code, since physically based parameter values are not available. However, the code includes the possibility of considering some direct penetration of rainfall through soil discontinuities, which produces a similar effect. By using two options for the possible concentrated recharge (it is assumed to increase as soil humidity decreases, with the maximum recharge for dry soil, when soil discontinuities are larger), adjusted average recharge for the observation period varies between 250 and 270 mm year^{-1}, or 44 and 47% of average rainfall in the same period. The extreme values are 30 mm for very dry years (1993 and 1994), and up to 800 mm for very wet years (1996).

Transient simulation of the cross section started using the calibrated steady state groundwater heads. The objective was to calibrate the RF and the storage coefficient in different observation wells, in or projected into the cross section. The calibration process was finished when both simulated head and discharge values matched the measured values within the error criterion, as defined by Anderson and Woessner (1992). It consists of calculating three values from the differences between the measured and the simulated head values: the mean error (ME), which is the mean value of the differences; the mean absolute error (MAE), which is the mean value of the absolute differences; and RMS, which is the standard deviation of the differences. All of these values were recorded during the calibration process. They have been used to identify the best fit presented in Fig. 8; it happens when the error is minimum and when the general trend of prolonged drainage due to a dry period and the recharge pulses are reproduced. The resulting calculated errors of the simulated vs measured data sets of the selected observation points range between 0.12–0.14 m for the

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ME, 0.16–0.5 m for the MAE, and 0.19–0.5 m for the RMS.

A sensitivity analysis was performed to assess the effects on the calibrated model of uncertainties in the aquifer parameter values, measured discharges, and head values. Initial estimates of specific yield ($S_y \equiv S_1$) were obtained from a large series of grain-size distributions from samples taken from the sandy aquifer. S_y ranged between 0.25 and 0.3 (Iglesias 1999), while the initial storage coefficient of the lower aquifer (S_2), estimated with well interference test data, ranged between 10^{-3} and 10^{-4}, and most of them were between 2.5×10^{-4} and 7×10^{-4}.

Some errors in reporting piezometric data were detected by comparing the heads from different water-level observation wells with accumulated deviation of rainfall from the mean value in the period. After filtering these possible errors (some could be safely corrected), transient simulation was performed with the water-level data from six observation wells over a period of about 11 years, which was divided into stress periods of 1 month. The regular monitoring water levels in shallow wells in the study area by the Geological Survey of Spain (ITGE/IGME) made this analysis possible.

Results of the Transient-Model Simulation

The calibrated, transient, cross-sectional model reproduces groundwater-head fluctuations within the error criterion, for the following conditions:

1. The S_y ranges between 0.06 and 0.22. The lowest values tend to occur in areas in which the water table is in the fluvio-marine sands (bi-modal grain size, with a fine-silica sand fraction) below the eolian sands, and the highest values occur in areas near the coast in which the water table is in the well-sorted eolian sands (unimodal grain size).
2. The input-recharge function (RF) is a fraction of the values obtained with the soil-water balance code. Near the coastal area the factor is 0.60–0.70, whereas near the centre of the area (El Abalario) this is approximately, 0.50–0.30 to the north and 0.40–0.75 to the east.

Since the period studied includes some average recharge sequences (mostly controlled by RF) and a significant dry period of well-defined water-table recession (Fig. 8) that is mostly controlled by S_y, the results can be considered quite reliable. Changes in S_2 and k_1 have a small effect on the results. Recharge is greatest on the coastal dunes (0.26–0.31 of average rainfall) and it decreases inland (0.22 of average rainfall around El Abalario).

The fact that the RF values obtained with a calibrated soil-water balance code appear as overestimated can be explained by (1) poorly known parameters, whose values can only be estimated through the calibration process, but cannot be checked against direct measurements, and (2) the fact that the soil-water balance calculates the water flow that leaves the soil in a downward direction, and the numerical simulation model of the cross section obtains net recharge to the aquifer, the difference being mostly because of phreatic transpiration by trees.

To obtain the 0.60 RF values by the recharge-calculation code it is necessary to introduce more concentrated recharge with increasing soil humidity (this is the opposite to what is assumed for concentrated recharge), and to use a doubled value for soil-water reserve, between 100 and 140 mm. This would be too extreme and unrealistic.

A clear relationship between annual values of recharge, R, and precipitation, P, has not been established. This is due to the influence of rainfall distribution inside a year and the influence of the water-table depth.

Model Application

Major impacts on groundwater resources are produced by groundwater abstraction and extensive eucalyptus forest. The calibrated model was applied to three changes in the groundwater pumping regime and two changes in the forest characteristics, which are described in the following two sections.

Effects of Groundwater Abstraction

To calculate in a simple manner the effect on the El Abalario water table of groundwater abstraction for irrigation and supply in the main pumping areas, it was assumed that the distortion produced in the flow field did not significantly change the regional flow pattern along the cross section. Each pumping well was assumed to be screened within the deep aquifer. The effect of pumping at a rate Q from the assumed unbounded, horizontally homogeneous, deep aquifer can be deduced from the unsteady state solution for a semiconfined (leaky) aquifer with constant-head conditions in the aquitard, which is the sand aquifer. The Hantush solution was used (Hantush 1964; Custodio and Llamas 1983).

At a given distance from the pumping well, where the induced drawdown in the deep aquifer was s, the increased vertical flow from the upper aquifer (acting as an aquitard) per unit area was $q = k'_1\ s$. The effect of pumping on the water table is approximately equivalent to the undisturbed situation with the recharge rate decreased by q. Consequently the effect of a pumping well on the cross section can be calculated by subtracting the appropriate value of q from the calibrated recharge at the corresponding distance from the well, assuming that the change in water storage in the aquitard due to elasticity can be neglected. The calculation can be simplified by assuming steady-state flow, since it is attained when $(r/B)^2 > 2\ u$ and $u < 0.03$ (Hantush 1964; Custodio and Llamas 1983, p 639), where $B^2 = T_2/(k'_1/b')$ and $u = r^2S_2/(4T_2\ t)$, in which r = distance from the

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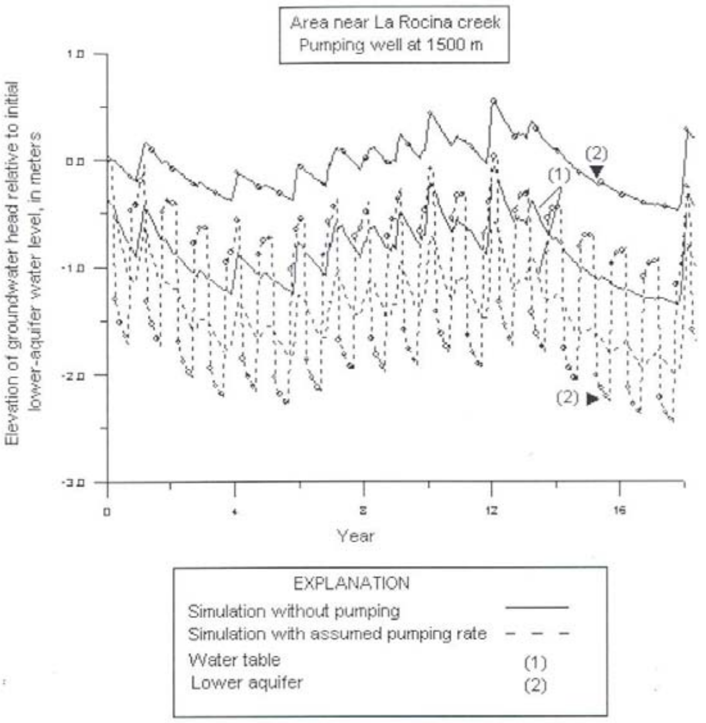

Fig. 9 Water-table and deep-aquifer piezometric level (below initial deep-aquifer water level) over 18 years at a point near La Rocina Creek in the irrigated area, under natural conditions, and as affected by groundwater abstraction of 160 L s^{-1} for 6 months each year at a distance of 1.5 km from La Rocina Creek

observation point to the well, t = elapsed time, and b′ = aquitard thickness.

This means that $t > S_2 b'/(2 k'_1)$ and $t > 0.12 T_2/(r^2 S_2)$.

In the least favorable conditions under consideration ($S_2 = 10^{-3}$ and 10^{-4}; $b' = 30$ m; $k'_1 = 0.002$ m day^{-1}; $T_2 = 500$ m^2 day^{-1}; r = 6 km), t is less than a few tens of days. This means that the simplified De Glee (or Jacob–Hantush) formula for steady state can be used (Custodio and Llamas 1983).

To study the effect of groundwater abstraction on the discharge to La Rocina Creek and to the shallow lagoons, three scenarios of increased aquifer pumping were considered. In each case a convenient set of hydraulic-parameter values was selected, based on existing data, measured head fluctuations, and spatial head differences in nearby monitoring piezometers (Trick 1998). This allows q to be obtained for diverse hypotheses at the desired distance from the wells. The vertical cross-sectional model was applied by using the 18-year recharge functions and the set of hydraulic parameters, starting from the steady-state solution at year 0, which corresponds to 1978. The first simulation represents the natural situation and the second the disturbed situation by pumping at the rate Q from each deep well.

The reference situation, as described in the Introduction, represents the average actual abstraction rate in the 1990s. Close to the starting period of simulation the abstraction rate was much lower, which means that the effects of groundwater exploitation have been increasing. This implies that the adjusted recharge has decreased for the same rainfall during the simulation period. Since calculated recharge values are used, this effect does not influence the study of changes in intensity of exploitation. The three scenarios are considered as follows. The sites do not correspond to the cross section but to relevant locations to which the recharge function and appropriate hydraulic parameters are applied.

Scenario 1 considers the effect of pumping 160 L s^{-1} for 6 months each year (mid-spring to mid-autumn), near the El Rocío agricultural area (northwest corner of the southwest irrigated area, Sector IV), 1.5 km south of La Rocina Creek. The results are shown in Fig. 9 and refer to a site near La Rocina Creek in the perpendicular line from the well, where there is upward flow from the deep aquifer under initial conditions. There is a downward trend of groundwater levels, seasonal pumping produces large piezometric fluctuations, and the natural upward head gradient is temporarily reversed during the pumping period. The water table drops about 0.5 m after 18 years. This causes a 40% reduction in phreatic evapotranspiration and a reduction in outflow to La Rocina Creek, which becomes nil during the pumping period in the area close to the wells. If a dry period is defined by the water table being deeper than 1 m under natural conditions, this

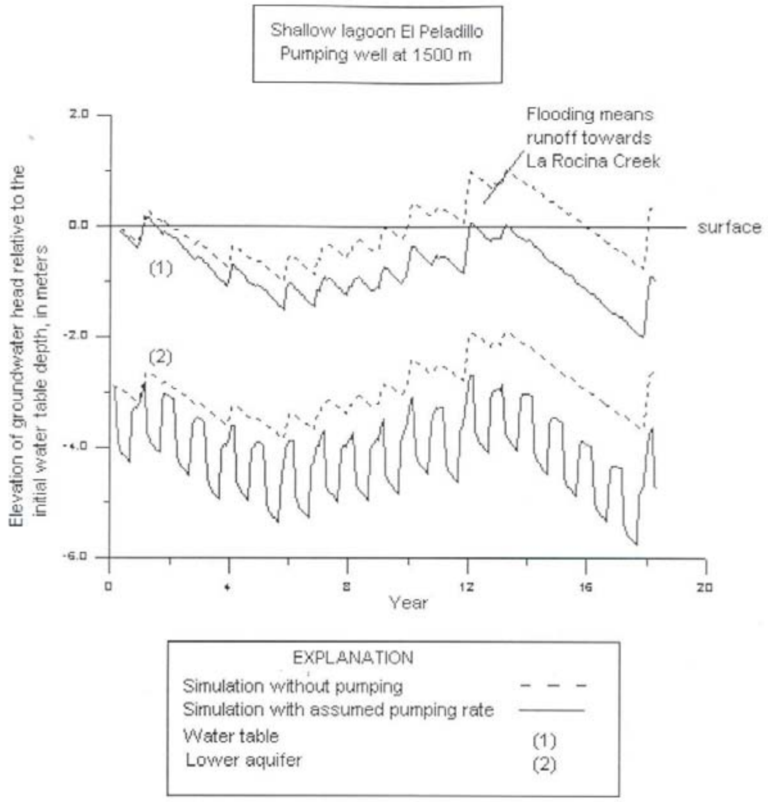

Fig. 10 Water-table and deep-aquifer piezometric level below initial water-table elevation over 18 years at a point near El Peladillo (centre of the area), under natural conditions and as affected by a groundwater abstraction of 160 L s^{-1} for 6 months each year, at a distance of 1.5 km. The water table may be above the reference level, due to the microtopography of the residual dune landscape

occurs about 40% of the time, whereas under the simulated disturbed conditions it increases to close to 90%.

Scenario 2 is similar to scenario 1, but the wells are now in the southwest corner of the southwest irrigated area (Sector IV) of El Rocío (El Alamillo). This is a recharge area where pumping may affect the shallow temporary lagoons. The effect at 1.5 km from the wells is shown in Fig. 10. Assuming that the phreatic lagoons are dry when the water-table elevation with respect to the reference level is 0.0 or −0.5 m under natural conditions, this occurs 0.6 to 0.25 of the time (observed data); however, under the simulated disturbed conditions this will occur 0.95 to 0.7 of the time.

Scenario 3 considers current conditions of pumping (50 L s^{-1}) in Mazagón and an increase to 100 L s^{-1} to supply the expanding tourist area during the two-month summer season. The effect 1 km away is shown in Fig. 11; it is negligible about 3 km away.

Effect of Forest-Cover Change

Starting from the calibrated solution for the eucalyptus forest between El Abalario and La Rocina Creek shown in curve "a" of Fig. 12, the cross-sectional model was then applied to the case in which the extensive eucalyptus plantations have been eliminated and not replaced with other deep-rooted vegetation, except for a strip of land 500 m wide along La Rocina Creek, which has been preserved since it contains natural species of flora in the gallery (riparian) forest (Fig. 12, curve "b"). The initial parameter values which control root uptake by natural vegetation from the phreatic layer were chosen as in former studies (ICE 1992) after checking them with a sensitivity analysis. The simulation results indicate major effects to the phreatic layer around La Mediana, between Rivetehilos and La Rocina Creek. By the end of the 18-year-long simulation period the phreatic level rose to about 3 m above the land surface near La Rocina Creek. This means that in real terms there is an increase of discharge into the creek of about 30% through old channels. These old channels, which are very flat and had practically disappeared beneath the eucalyptus forest, could, however, be identified in detailed surveys and respond to old situations (Sousa and Garcia Murillo 1999). This is at most an intermittent situation.

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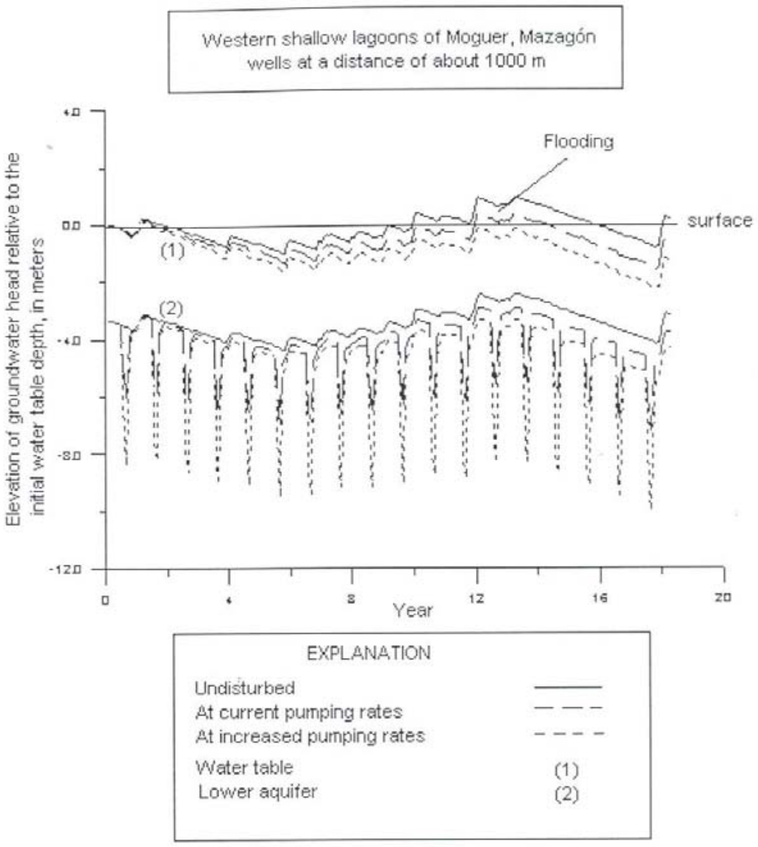

Fig. 11 Water-table and deep-aquifer piezometric level below the initial water-table elevation over 18 years in the area of Mazagón (close to Laguna de Moguer lagoon), under natural conditions and with groundwater pumping rates of 50 and 100 L s^{-1} during the two summer months

The following two other scenarios have been considered:

1. The eucalyptus forest is replaced by native plants capable of maximum phreatic evapotranspiration of 200 mm $year^{-1}$ (instead of 525 mm $year^{-1}$ for eucalyptus), with a maximum extraction depth for phreatic evaporation of 2 m, instead of 5 m for eucalyptus (Fig. 12, curve "c").
2. Native vegetation is re-established along the whole cross section (Fig. 12, curve "d"). This may produce phreatic evapotranspiration from close to El Abalario to the surroundings of La Rocina Creek.

Restoration of natural vegetation results in establishing a very shallow water table, with more permanent lagoons and marshy lands, but the effect is negligible between El Abalario and the coast.

Concluding Remarks

An improved assessment of discharge to La Rocina Creek and groundwater uptake by eucalyptus roots would enhance model calibration and would therefore reduce calculation uncertainties. Groundwater discharge by the eucalyptus trees has deeply disturbed the natural water-flow pattern of this aquifer system for a long time, so the system has adapted to these circumstances. The effects of changes in vegetation cover could be very important, and therefore they should be monitored and be taken into account for groundwater management. The plan to eradicate the eucalyptus plantations is a major change that affects groundwater recharge and the transient nature of the lagoons. The extent of groundwater extraction for irrigation purposes should consider its effects on the discharge system of the La Rocina Creek zone and the shallow lagoons. Since pumping is concentrated in the more permeable layers of the lower aquifer, this will affect a large area through a small but significant lowering of the water table, with detrimental effects on the lagoons and on the flow of La Rocina Creek, if there

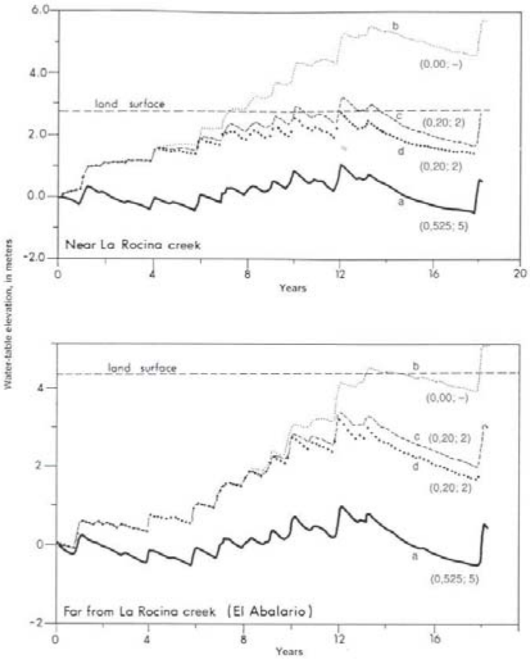

Fig. 12 Effect on the water-table elevation of eradication and substitution of the eucalyptus forest along the simulated cross section, near the centre of the area (El Abalario) and near La Rocina Creek. Curve (*a*) signifies the calibrated situation with eucalyptus forest and some remnants of native vegetation between El Abalario and La Rocina Creek; curve (*b*) shows the results of deforestation, leaving the land free of phreatophytes, except in a 500-m-wide strip along La Rocina Creek; curve (*c*) corresponds to the results of restoring native vegetation where eucalyptus trees were indicated; and curve (*d*) shows the same situation as for curve (*c*) but introducing native vegetation in the whole area, including places where the water table is shallow enough to support phreatophytes. The figures associated with each curve indicate, respectively, the maximum phreatic evapotranspiration in meters per year and the maximum depth of phreatic evapotranspiration, in meters

is increased groundwater exploitation in the irrigated areas. However, replacing the eucalyptus trees with native vegetation could significantly raise the water table under the eucalyptus forest and increase the flow of La Rocina Creek. Thus, long-term transient effects and widespread spatial variations in recharge should be taken into account when impacts of groundwater exploitation are evaluated, since trends can be temporarily disguised and reversed in wet periods. This may be interpreted as the absence of negative impact, when there is a drawdown and the frequency and duration of high water table periods are decreased. Simple analyses of short-term monitoring results may produce misleading results.

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