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Upgrading aquifer test interpretations with numerical axisymmetric flow models using MODFLOW in the Doñana area (Spain)

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ABSTRACT

Though axisymmetric modelling is not widely used it can be incorporated into MODFLOW by "tricking" the grids with a log-scaling method to simulate the radial flow to a well and to upgrade hydraulic properties. Furthermore, it may reduce computer runtimes considerably by decreasing the number of dimensions. The Almonte-Marismas aquifer is a heterogeneous multi-layer aquifer underlying the Doñana area, one of the most important wetlands in Europe. The characterization of hydraulic conductivity is of great importance, because this factor is included in the regional groundwater model, the main water-management support tool in the area. Classical interpretations of existing pumping tests have never taken into account anisotropy, heterogeneity and large head gradients. Thus, to improve the characterization of hydraulic conductivity in the groundwater model, five former pumping tests, located in different hydrogeological areas, have been modelled numerically to represent radial flow in different parts of the aquifer. These numerical simulations have proved to be suitable for reproducing groundwater flow during a pumping test, to corroborate hypotheses concerning unconfined or semi-confined aquifers and even to estimate different hydraulic conductivity values for each lithological layer drilled, which constitutes the main improvement of this model in comparison with classical methods. A comparison of the results shows that the values of the numerical model are similar to those obtained by classical analytic techniques but are always lower for the most permeable layer. It is also clear that the less complex the lithological distribution the more accurate the estimations of hydraulic conductivity.

Key words: Doñana, hydraulic conductivity, MODFLOW, numerical modelling, pumping test

Mejora de las interpretaciones de ensayos de bombeo con modelos numéricos de flujo simétricos respecto de un eje en el área de Doñana usando MODFLOW

RESUMEN

La modelación simétrica respecto de un eje puede utilizarse en MODFLOW, manipulando el mallado con un método de escalado logarítmico, para simular el flujo radial hacia un pozo y obtener así una mejor estimación de las propiedades hidráulicas. Reduciendo el número de dimensiones se reduce también el tiempo de simulación. El acuífero Almonte-Marismas constituye un acuífero multicapa heterogéneo que subyace bajo el área de Doñana, uno de los humedales más importantes de Europa. La caracterización de la conductividad hidráulica es importante ya que es utilizada por el modelo de flujo subterráneo regional que constituye la herramienta de gestión del agua en la zona. Las interpretaciones clásicas de los sondeos existentes no tenían en cuenta anisotropía, heterogeneidad o grandes gradientes, por eso, para mejorar la precisión de los valores de conductividad hidraúlica en el modelo de agua subterránea se utiliza una ecuación de gobierno en coordenadas cilíndricas en cinco ensayos de bombeo antiguos situados en diferentes zonas del acuífero. Los resultados obtenidos se han comparado con otras interpretaciones previas. Las simulaciones numéricas han demostrado ser adecuadas para reproducir el flujo subterráneo en un ensayo de bombeo, para cotejar comportamientos semiconfinados o libres e incluso, para estimar valores diferentes de conductividad hidráulica de cada una de las litologías perforadas, lo que constituye la mayor ventaja respecto a los métodos tradicionales. Los nuevos resultados son similares a los obtenidos por métodos tradicionales pero siempre más bajos que éstos en la capa de mayor permeabilidad. En general a menor complejidad mejor estimación se obtiene.

Palabras clave: conductividad hidráulica, Doñana, ensayo de bombeo, modelación numérica, MODFLOW

Introduction

Available finite-element and finite-difference numerical programs have been successfully used to analyse pumping-test data, thus improving the credibility of aquifer test results when compared to the many limitations of traditional analytical integral and empirical equations (Walton, 2008; Yeh and Lee, 2007).

Moreover, upgrading aquifer test analyses reduces uncertainties concerning the surrounding groundwater flow and transport model calibration, optimization and uniqueness (Walton, 2008). Nevertheless recent theories and software are still frequently ignored, with the result that confidence in aquifer test results is less than might be desired despite the considerable attention that has been devoted to acquiring and interpreting such data (Yeh and Lee, 2007).

Under homogeneous conditions and in the absence of any regional hydraulic gradient, groundwater flow towards an extraction well or away from an injection well presents radial symmetry. This reduces the governing flow equation by one dimension. For numerical simulations, which can be encumbered by lengthy computer runtimes, reducing the number of dimensions can substantially reduce runtimes but, surprisingly, are not commonly used. Although there are a large number of publications and text books describing applications of models in aquifer tests to estimate hydraulic properties and determine heads and flows in the vicinity of a well (Barrash and Dougherty, 1997; Lebbe and De Breuck, 1995; Lebbe, 1999; Johnson *et al.,* 2001; Samani *et al.,* 2004; van Meir and Lebbe, 2005; Halford, 2006), axisymmetric modelling is still not used routinely (Langevin, 2008). Its lack of widespread use can be explained by the limitations related to the assumption of radial symmetry and the common perception that specialized computer programs are required to simulate axisymmetric flow.

The finite-difference method can be used to solve a radial form of the governing flow equation. The original MODFLOW program (Mcdonald and Harbaugh, 1988) and subsequent versions (Harbaugh and McDonald, 1996; Harbaugh *et al.,* 2000; Harbaugh, 2005), however, are based on a rectangular finite-difference grid. Therefore, this commonly used program cannot be directly used to simulate axisymmetric flow. For this reason investigators have developed simple methods for tricking MODFLOW into simulating axisymmetric flow (Reilly, 1984; Rutledge, 1991; Anderson and Woessner, 1992; Reilly and Harbaugh, 1993; Samani *et al.,* 2004; Romero and Silver, 2006). MODFLOW calculates the hydraulic conductance between cells by averaging transmissivity values. For axisymmetric flow, the hydraulic conductivity varies linearly between two adjacent nodes; therefore, the use of harmonic averaging (derived for piecewise variation in transmissivity) underestimates the conductance between two nodes. Transmissive and storage properties are increased with radial distance from the pumping well to simulate the increasing flow area and storage volume. Logarithmic averaging has been shown to provide the correct head distribution for this linear variation in transmissivity (Goode and Appel, 1992). Samani *et al.* (2004) embedded a log-scaling method (LSM) into MODFLOW-2000 to simulate axisymmetric flow. The LSM is based on a set of scale factors obtained by comparing the governing equations in Cartesian and cylindrical co-ordinates. Samani *et al.* (2004) tested the LSM with several theoretical radial-flow problems of varying complexity and we have chosen this method to upgrade some hydraulic conductivity values in the Almonte-Marismas aquifer.

The Almonte Marismas aquifer underlies the whole area of Doñana and is a heterogeneous multi-layer aquifer, containing alternating layers of sediments of greater or lesser permeability. During the 1970s more than 400 characterization pumping tests were conducted in the area by the Regional Institute for Agricultural Development (IRYDA) as part of the Almonte-Marismas Agricultural Transformation Plan promoted by the United Nations Food and Agriculture Organization (FAO). Details concerning these tests are described in FAO (1970; 1975) and IRYDA (1976).

The information available from the pumping tests characterizes hydraulic conductivity distribution, which is one of the inputs needed to build the regional groundwater model. This support tool is used for water management in the Doñana area, an important wetland where groundwater supplies are critical to the maintenance of water levels and a great variety of ecosystems. Hence water-management decisions must be based on as much accurate information as possible. Interpretations of pumping tests were originally based on the graphical analysis of drawdowns over time, based on studies made by Theis (Theis, 1935) for confined and unconfined aquifers. This assumed strict conditions such as zero well diameters, fully penetrating wells, no loss, infinite, homogeneous and isotropic aquifers and constant pumping rates. Parameters were arrived at through the manual adjustment of formula curves. The limitations to the interpretation of these traditional aquifer tests included the need for subjective decisions as to which portion of measured aquifer test data should be matched to type curves or straight lines, what method should be used and/or what role parameter estimation should play in aquifer test analysis.

Subsequent to the original analyses made in the 1970s other interpretations of some of the pumping tests were undertaken by several authors (Palancar and Cantos, 1996; Trick, 1998; Vázquez, 1999) by applying various methods such as the manual or automatic adjustment of formula curves or by using diverse computer codes (Hydralogic, 1989; Carbonell *et al.,* 1997; Pibe, 2007; Custodio *et al.,* 2009) and assuming different interpretative models. The numerous different results obtained in all these works indicated a significant divergence in estimations of hydraulic properties (i.e. transmissivity and storativity/specific yield). Guardiola-Albert and Garcia-Bravo (2008) compared several interpretations, analysing the sources of these divergences, and concluded that in general all of them obtain the same orders of magnitude for hydraulic conductivity as the original IRYDA estimations. In detail, however, the assumptions and simplifications in the geometry and physical characteristics of the aquifer and wells entail inaccuracies. All these reasons therefore led us to the conclusion that pumping tests in the Almonte-Marismas aquifer should be reanalysed and hydraulic conductivity estimations improved by taking into account certain real aquifer conditions, such as the anisotropy and heterogeneity of the environment and the large head gradients in the vicinity of the well.

Within this context, this paper describes the application of two-dimensional numerical-flow modelling to check the estimations of hydraulic conductivity derived from the pumping test data in the Doñana area referred to above. Axisymmetric flow is simulated by adjusting several MODFLOW input parameters to account for the increase in flow area with radial distance from the extraction well, as suggested by Samani *et al.* (2004). Modelling results are discussed and compared with traditional interpretations, emphasizing their success and improvements made by numerical methods to the confidence level of estimated hydraulic conductivity. To illustrate the discussion, the results of five test problems situated in different hydrogeological areas of the aquifer are described.

Study site and pumping tests

Many studies and previous works have described the importance of groundwater in Doñana (Suso and Llamas, 1990, 1993; Custodio and Palancar, 1995; Muñoz-Reinoso, 2001; Custodio *et al.,* 2009). The Doñana area contains four different types of ecosystem: marshes, aeolian mantles, coastal lines and the Guadalquivir river estuary (Montes *et al.,* 1998), which are completely contained in the Almonte-Marismas aquifer (2,400 km^2). This Spanish natural enclave is one of the most important wetland reserves in Europe and includes national and natural parks, a biosphere reserve, a Ramsar site and a Natural World Heritage site. Hence it needs appropriate water management in order to control and maintain the needs of the environmental system, the irrigated lands and the local population and visitors.

The Almonte-Marismas aquifer is located within the provinces of Seville and Huelva in the region of Andalusia in southwest Spain. It is hydrologeologically bounded by the river Guadalquivir to the east, outcrops of impervious marls to the north, the river Tinto to the west and the Atlantic Ocean to the south. Its geology and lithostratigraphy have been described by several authors, such as Viguier (1974), Civis *et al.* (1987), Mayoral and Pendón (1986; 1987) and Salvany and Custodio (1995). It is essentially made up of Plio-Quaternary detrital series such as clay, silt, sand and gravel and aeolian sands (Figure 1).

Salvany and Custodio (2005) identified four separate units: aeolian, deltaic, alluvial and marshland. The aeolian and deltaic units are separated from the delta and marshland by a NNE-SSW fault. Blue marls deposited in the Upper-Miocene (Viguier, 1974; Sierro, 1984; Civis *et al.,* 1987) constitute the impervious bottom of the multilayer aquifer. The Almonte-Marismas aquifer is formed basically of basal sand, silts and the aeolian mantle and behaves as unconfined to the north, west and southwest. To the east and southeast it is confined by the low-conductivity marsh materials that lie above it. Both parts are hydraulically connected (Suso and Llamas, 1990, 1993; Llamas, 1993; Custodio and Palancar, 1995) and the area between them is semi-confined in its behaviour (Custodio and Palancar, 1995; Custodio, 2005).

The IRYDA carried out hydrogeological studies to promote an economic development based on irrigation in the area. Within this context, between 1966 and 1974, 430 pumping tests were conducted in wells bored to exploit the aquifer. These pumping tests have been used in most subsequent hydrogeological studies to determine the hydraulic conductivity of the deep porous formations in the area. Hydraulic conductivity was estimated using the Theis-Jacob equation (Theis, 1935) and it turned out to be highly variable in space, both horizontal and vertical, due to the distribution and the heterogeneity of the rocks enclosing the natural environment. From these pumping tests, and others undertaken more recently, five pumping wells were selected to illustrate the present work. Each has particular characteristics due to its location in the aquifer and the different layouts of the local rock formations. Three of the wells are situated in the unconfined part of the aquifer (Abalario, Mazagón and III-3-10) and two in the confined area (Mari López and I-6-5). Most of the pumping tests consisted of ten hours' pumping followed by 10 hours' recovery, except for that at El Abalario, which consisted of 42 hours' pumping and 42 hours' recovery. No recovery was registered in the

Mari López test. It must be emphasised that none of them is a completely penetrating well and that most of them are equipped with more than one filter so as to be able to extract water from different lithologies in the same bore. A description of the selected pumping tests and their characteristics is detailed below (Figure 2).

The El Abalario well is located in the aeolian unit (Salvany and Custodio, 1995) and was subjected to the most complete pumping test conducted in the aquifer, with 42 hours' pumping and 42 hours' observations during the recovery time, both in the pumping well and in three piezometers. The lithological column (Figure 2) shows a sequence of fine sand (0-90 m) over a more permeable level containing gravel. The same structure appears in the rest of the piezometers at slight differences in depth. Thus there are two formations with different hydraulic conductivities: an upper one, made up of fine sand, with low values, and a lower one, of gravel, with higher values. This more permeable layer dips towards to the southeast, and forms the hydraulic connection with the alluvial level below the marshes, thus increasing storage in that direction. The dynamics of this area could therefore be interpreted by the Theis model at the lower level, but the upper sands act as an aquitard and point to the Hantush model as being a more reliable approach. Two of the pumping tests selected, El Abalario and Mazagón, are located in this aeolian landscape.

The Mazagón well is located to the northeast of the town of Mazagón, on the western side of El Abalario (Figure 1). A single filter simplifies the mathematical simulation. The lithological column (Figure 2) reveals 45 m of fine sand above a two-metre level composed of clay, sand and gravel, and a lower, highly permeable formation made up of gravel and coarse sand, in which the filter is placed. The existence of a narrow separating level determines the hydrological behaviour as being either confined or unconfined. The drawdown-time data represented in a semi-logarithmic plot show a changing slope for 10 min, which remains stable thereafter. This probably indicates different drainage processes or the emptying of the water column.

The III-3-10 well is located to the north of the town of El Rocio near the Venta del Caño stream, where the basal sand formation crops out, but not far away from the limit between the unconfined aquifer and the marshland (Figure 1). The lithological description (Figure 2) is basically a series of fine, medium and coarse sands with a one-meter level of clay-sand on the surface and two metres of sandy-clay right above the filter position. This clay layer could affect the vertical hydraulic conductivities considerably, slowing drainage from the upper sands and determining the aquifer's behaviour as confined or semi-confined. This lithological description is not as simple as that of Mazagon or El Abalario, which are situated on the west side of the Abalario elevation, indicating that to the east, where the marshes begin, the deep layout and groundwater dynamics become more complex.

The Mari López well is located in a completely confined area of marshland (Figure 1). It is composed of mud and clay sediments that cover an isolated, salt-water aquifer composed of cobbles and gravel to a depth of 60 m. Beneath it lies another clay level, under which are the productive water levels equipped with three filters. Figure 2 shows the lithology of the well and the position of the filters.

The I-6-5 well was bored during the Almonte-Marismas Agricultural Transformation Plan, in the so called I-sector on the right-hand side of the Guadiamar River (Figure 1). According to the norms of this plan the river was channelled to exploit the water resources more efficiently, modifying its natural course and consequently lessening its contribution to the marshes. Nevertheless, the groundwater flow is still considerable due to the deeper levels of the aquifer, identified as old alluvial deposits buried under the marsh deposits (Salvany *et al.,* 2001). As shown in Figure 2, below 14 m of clay there is an initial level of fine sands, followed by a stretch of gravel. The productive levels are separated by fine-grained sand or clay materials. Just as at the Mari López well, the behaviour of the rest of the aquifer throughout this area is clearly confined.

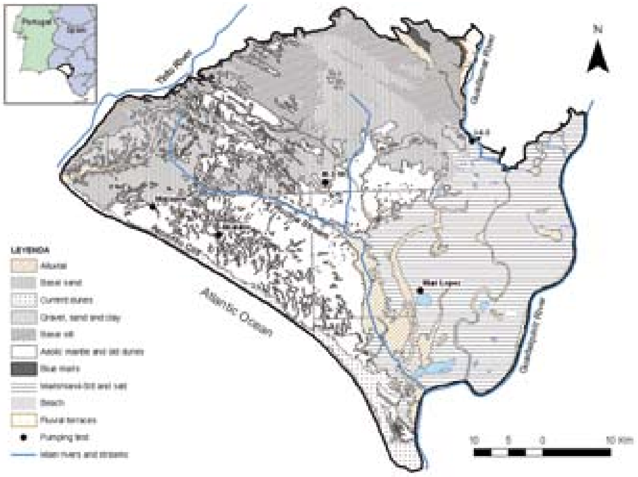

Figure 1. Situation of the aquifer main lithological formations and well sites.

Figura 1*. Situación del acuífero de los pozos y principales litologías.*

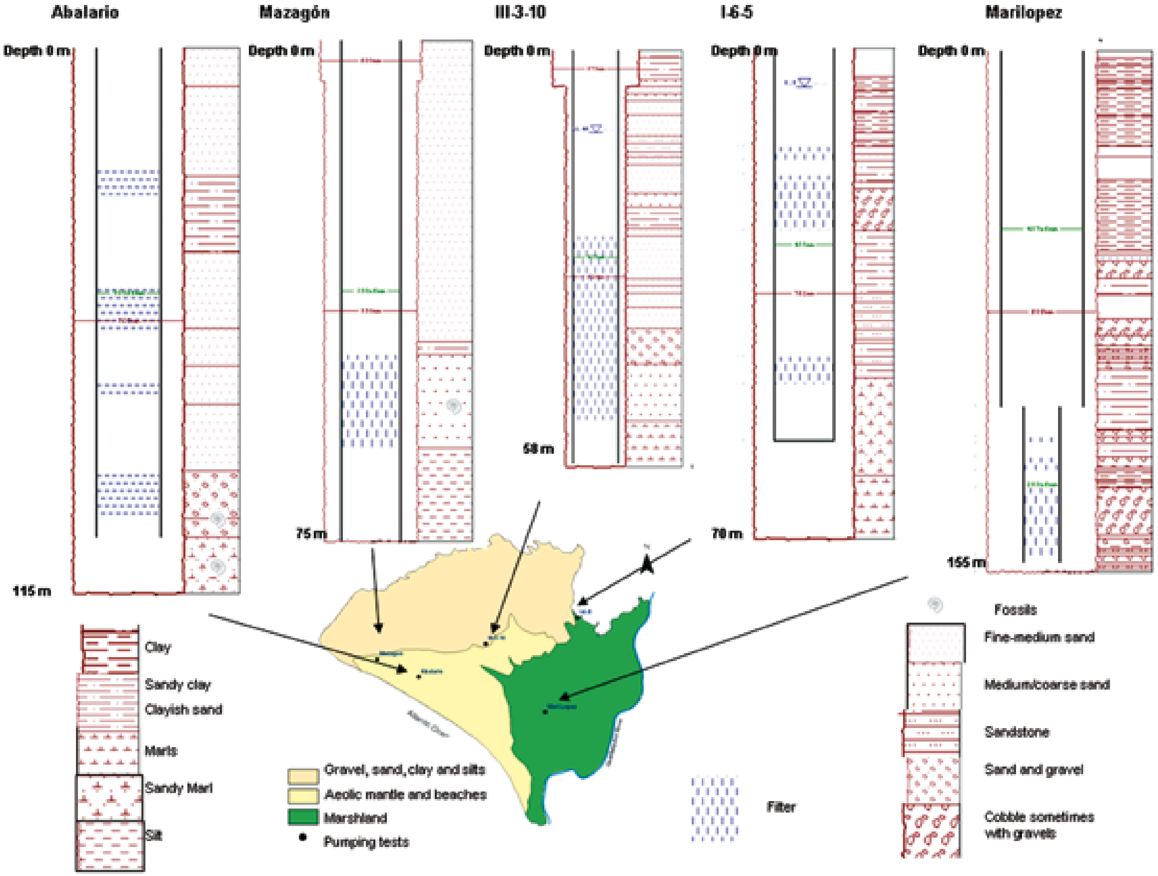

Figure 2. Location and lithological descriptions.
Figura 2. *Situación y descripciones litológicas.*

Methods

Our approach to the reassessment of the hydraulic conductivity for the five selected pumping tests was based on the work carried out by Samani *et al.* (2004). The method consisted of creating two-dimensional models of radial sections of the aquifer affected by the pumping well using Visual MODFLOW v.4.2. (Visual MODFLOW2006). The transformations suggested by Samani *et al.* (2004) are needed to express a symmetric problem in cylindrical co-ordinates. This allowed us to solve easily two dimensional problems of a symmetric nature, as in the case of pumping tests, thus improving the resolution of the flow near the well thanks to a more precise discretization. The following information was required to construct the model: geological data, layer shape and thicknesses, piezometric data, geometry of the well, hydraulic conductivities, storage coefficients, porosities and pumping rates. The reanalysis procedure in each of the selected pumping tests included the following steps:

1. Geometry: The number of rows, columns and layers were decided upon according to the depth of the well and the filters in place. The lithological column and technical characteristics of each of the points served as a basis for the construction of the model. The number of columns, rows and layers were assigned according to the degree of precision required. Visual MODFLOW creates a *.VMG file that contains a simple meshing with the information entered. This file was modified with previously calculated positions as Visual MODFLOW does not import mesh positions with decimals. The x-axis values for end-points were defined by the radius of the well and the radius of influence of the pumping. The values of x entered into Visual MODFLOW were logarithmic: x(MODFLOW) = ln(r). The y-axis was taken to be unitary; the cell size in y direction was 1 m, which makes up a circular sector of one single section. The number of divisions on the z-axis was marked according to the depth of the well. The thickness of the rows varied outwards, from the thinnest next to the well (0.2 mm minimum) and thence increasing at a rate of 1.4 so as to minimize errors due to non-horizontal flow and a high piezometric gradient near the filters.

2. Hydraulic parameters: Following the guidelines of Samani *et al.* (2004) the hydraulic parameters were transformed to simulate cylindrical co-ordinates. These were applied to hydraulic conductivities in the three directions (K_x, K_y, K_z) and storage (S_s for confined layers and S_y for unconfined). K_x and K_y were presumed to be the same as isotropy in the horizontal direction. K_z varied since anisotropy in the vertical is permitted. And, as required in Samani's report, the values of S_s, S_y and K_y must be processed by a multiplicative factor computed depending on the distance to the well:

$$f = \frac{e^2 x_2 - e^2 x_1}{2(x_2 - x_1)} \qquad (1),$$

   where x_1 and x_2 represent values of the x co-ordinate in two adjacent columns.
3. Pumping well: Each model was assigned a column (column 1) to represent a pumping well with a given extraction rate. This well was also the observation point with measured drawdowns. To consider the first column as the pumping well, an exaggerated K_z of 10^9 m/d was assigned so as to reproduce the effect of the well. At the filter level, K_x and K_y were assigned to be a tenth of the K_x and K_y values in the adjacent column and a very low value in the levels not equipped with filters. In this well column the porosity was equal to 1 to simulate the hole. The initial piezometric level required for all the cells was equal to the value measured in the field at time zero.
4. Pumping rates: Flow values had to be processed according to the equations described in Samani *et al.* (2004). Filter positions in the wells had to be checked and pumping flow rates translated into cylindrical co-ordinates with:

$$Q_{\text{modflow}} = -\frac{Q_{\text{real}}}{2\pi} \qquad (2)$$

5. Calibration: The groundwater flow equation was subsequently solved by applying extraction flow and using Visual MODFLOW resolution tools. Initially, hydraulic parameter ranges were chosen from previous studies conducted in the area (Palancar and Cantos, 1996; Trick, 1998; Vázquez, 1999; Guardiola-Albert and García-Bravo, 2008). Observed and calculated piezometric levels were compared and hydraulic conductivities calibrated to reach a best fitting. The resulting hydraulic conductivities had to be back-transformed according to Equation (1).

The main advantages of this method are that: (i) it takes into account the existence of the well, assigned to the first column of the two-dimensional model; (ii) it distinguishes the different lithologies at depth; (iii) it takes into account the existence of different filters; and (iv) it avoids losses at the edges of the grid due to the broader discretization. The results obtained from applying numerical modelling at various hydrogeological sites are discussed and compared with traditional interpretations, emphasizing its success and improvements to the confidence level of estimated hydraulic conductivity by using models more attuned to real physical characteristics. This method works for hydraulic conductivity, although it was impossible to simulate piezometers in the proposed two-dimensional models. Cylindrical co-ordinates imply that observation wells, sited at any distance from the pumping well, would act as a cylindrical hole at the same distance in any direction. As a consequence of this artificial fact it was not possible to estimate storage coefficients, as observation data are necessary to assess the storage coefficient.

Results

The adequacy of the fittings are illustrated with different graphics (Figure 4). The mean error (ME) and mean absolute error (MAE) of the predictions (Table 6) were computed as:

$$ME = \frac{1}{N_t}\sum_{t=1}^{N_t}\left[h_{\text{modflow}}(t) - h_{\text{observed}}(t)\right] \qquad (3)$$

$$MAE = \frac{1}{N_t}\sum_{t=1}^{N_t}\left|h_{\text{modflow}}(t) - h_{\text{observed}}(t)\right| \qquad (4)$$

where h is the piezometric level, either calculated (h_{modflow}) or measured (h_{observed}), and N_t is the number of times that the pressure was measured.

The results for the five pumping tests were as follows:

El Abalario: El Abalario was the most complete pumping test carried out in the area, including measurements made at three piezometers apart from the pumping well. Nevertheless, these piezometric measurements were not used in our numerical model, as the method applied cannot simulate piezometers. To include them would mean that there were empty cylindrical sectors at those distances from the pumping well, resulting in an unreal modelling. This is the main constraint when using a two-dimensional simulation in cylindrical co-ordinates.

Different models with different hydraulic parameters were considered for the calibration but, taking into account the measured drawdowns and the lithology in question the model in Figure 3 was chosen as the best representation of the area around the El Abalario well. Basically it shows a sequence of different-sized sands: an upper one of fine sand (0-8 m) and an intermediate sand package (8-90 m) lying over a more permeable level of gravels (90-100 m). To simplify the model the first and second packages were treated as one. Consequently, the hydraulic conductivity distribution (Figure 3) was arranged in two different parts: the S and S_s values assigned were 4.45 10^{-4}, 7 10^{-6} m^{-1} and 5 10^{-6}, 5 10^{-7} m^{-1} for the upper and lower part respectively, whilst the hydraulic conductivities that best fitted the real behaviour were $K_{x,y}$ = 0.00386 m/d for the upper part and $K_{x,y}$ = 2.84 m/d and K_z = 2.84 m/d for the lower one. $K_{x,y}$ in the more transmissive level was the most sensitive value.

The differences between the calculated versus and the measured values (Figure 4) could be attributed to head loss in the well. The calibration errors are ME = -0.48 m and MAE = 1.6 m. During the simulated pumping test the model shows that at the beginning of pumping a shower effect from the upper layers to deeper zones took place, represented by low velocities. Vertical ascendant flows due to the semi-confined behaviour of the deeper layers were also observed.

Mazagón: The lithological column shows a thin clay level with sand and gravel right above the filtered level. Therefore, two approaches were applied: (i) a two-layer model and (ii) a three-layer model.

(i) In the two-layer model the clay level is disregarded and the model consists of an upper level of fine sand and a lower one of gravel and small gravel, equipped with filter (Figure 3). The best solution reached with this simpler model was with $K_{x,y}$ = 8.23 m/d for the lower layer and $K_{x,y}$ = 0.064 m/d for the upper layer. K_z ranged between 1.4 10^{-4} m/d in the upper layer and 0.013 m/d in the lower one. Despite this low K_z, the fitting of the modelled value is very similar to that of the measured one (Figure 4).

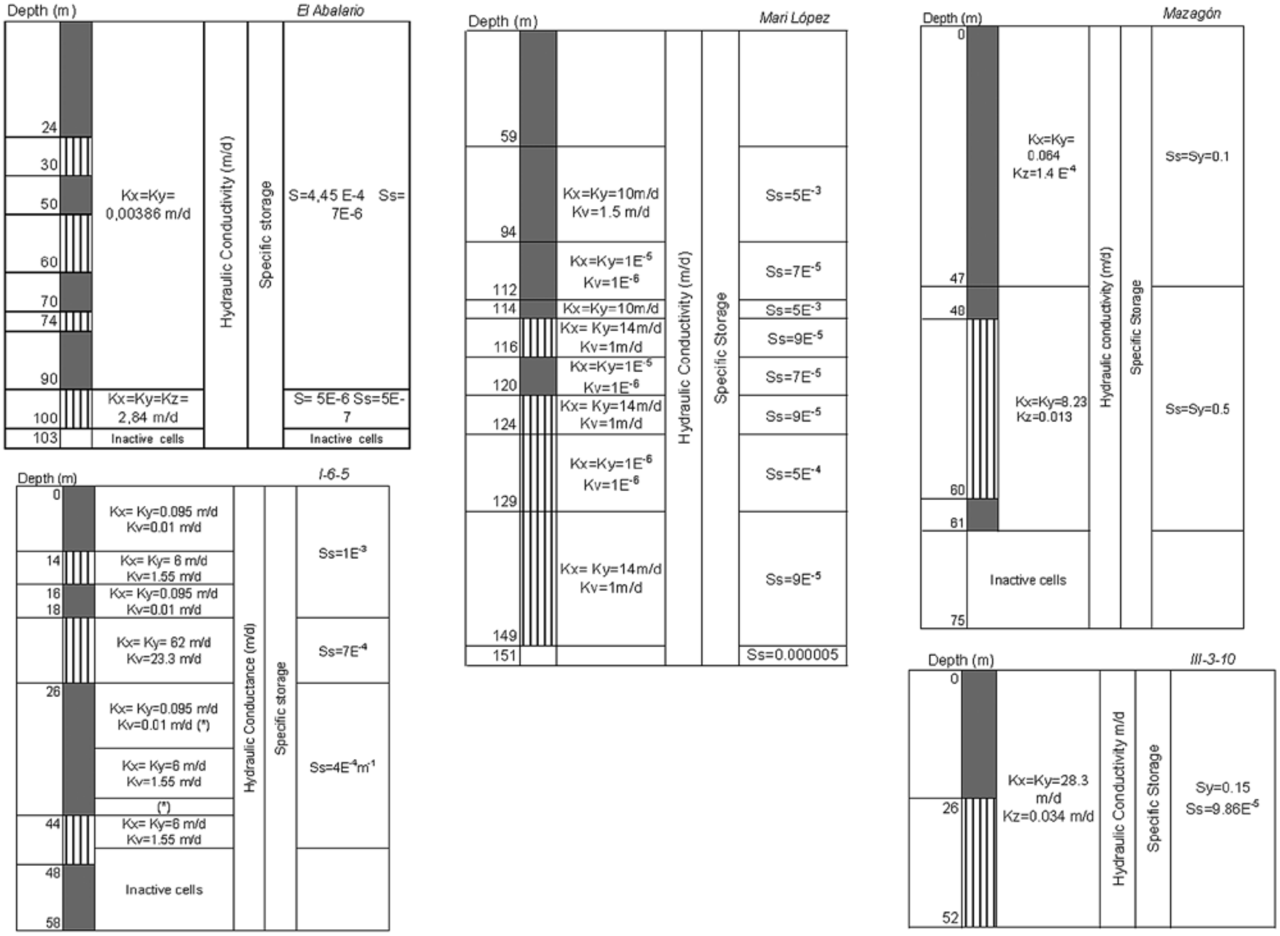

Figure 3. Hydraulic parameter values assigned in the best fittings (not to scale).
Figura 3. *Valores de los parámetros hidraúlicos asignados en los mejores ajustes. El esquema no está a escala.*

Sensitivity analyses reveal that $K_{x,y}$ is the most sensitive parameter. The calibration errors were ME = 0.10 m and MAE = 0.89 m.

(ii) The three-layer model does take the thin clay level between the main two packages into account. This determines the flow from the upper to the lower layer and so the hydraulic conductivity of the upper zone depends inversely on the hydraulic conductivity of the clay level. It is important to highlight the existence of these impervious levels, which can influence the hydraulic conductivity values of the more productive layers. In any case, $K_{x,y}$ obtained for the filtered layer with this three-layer model was also around 10 m/d. If the lower layers are taken to be confined layers the fitting improves for the same $K_{x,y}$ value. Despite the satisfactory fittings, the storage coefficients used to obtain them are too low to be realistic. When using other more realistic values the correlation between the calculated and measured values was not so good. Both features seem to be reasonable due to the clay level, which should act as a confining level and lower the storage coefficient value.

III-3-10: As with the Mazagón pumping test, two simulation models were made to take into account any possible differences arising from the interpretation of the lithological columns. On the one hand, a two-layer model was simulated in which a stretch of clays separates a higher layer of finer grain size from one with larger particles and on the other, a single-layer model considered the minimum spatial variability of sand.

(i) Two-layer model: initially the sand-clay level situated just above the filter was considered to be very important, so the model was divided in two areas, differentiating hydraulic conductivity and storage coefficient. The upper layer, containing more fine and medium-grained sand, was not equipped with any filter. In the bottom layer, packages of gravel, and sand and gravel become thicker, although the uppermost metres consist of fine and medium-grained sand. Each of the two layers was 26 m thick. The blue-marl formation constituted the impervious bottom. The storage coefficient also distinguished between two levels of 26 m, with the lower section having a higher porosity value. The calibrated hydraulic conductivities were: $K_{x,y}$ = 0.1 m/d for sand, $K_{x,y}$ = 28 m/d for gravel, S_s = 0.0015 m^{-1} for sand, S_s = 5 10^{-4} m^{-1} for gravel, S_y = 0.15 m^{-1} for sand and S_y = 0.15 for gravel.

(ii) Single-layer model: Another possible solution that was modelled assumed a single layer, thus disregarding the role of the small levels of fine sand (Figure 3). This was justified by the high flow rate that the well produces. It was considered that the lithology described at depth could be considered homogeneous enough to use one hydraulic conductivity and specific storage. The fitting in the graph in Figure 3 was arrived at with the following values: $K_{x,y}$ = 28.3 m/d, K_z = 0.034 m/d, S_s = 9.86 10^{-5} m^{-1} and S_y = 0.15.

The hydraulic conductivities for both models are very similar (28 m/d), so the simplest, with a single layer, was chosen as being more suitable. The fitting of the modelled value was very similar to that of the measured one (Figure 4). Sensitivity analyses revealed that $K_{x,y}$ was the most sensitive parameter. The calibration errors were ME = -0.16 m and MAE = 0.41 m.

Mari López: The graphic scheme in Figure 3 shows the discretization system. These rows have different thicknesses depending on the site and depth of the filters and represent a total borehole depth of 151 m. In response to the geological characteristics the model includes an impermeable clay layer of considerable thickness (60 m) on top, to which is assigned the same hydraulic conductivity as the lowest clay layer, equal to a very low value of 10^{-6} m/d. The calibration results for the hydraulic conductivity of the rest of the strata were 10 m/d for the salty aquifer, which was not very sensitive since this section has been sealed, and 14 m/d for the deepest fresh-water aquifer, the one being exploited. The vertical conductivities, K_z, were 1.52 m/d and 1 m/d for the salty aquifer and the exploitable sections respectively. The hydraulic conductivity of the sandy clays that separate the sections of the aquifer was calibrated to 10^{-5} m/d. Specific storage values assigned, from the surface were: clay $5 \cdot 10^{-4}$ m^{-1}, salty aquifer $5 \cdot 10^{-3}$ m^{-1}, sandy clay $7 \cdot 10^{-5}$ m^{-1} and fresh-water aquifer $9 \cdot 10^{-5}$ m^{-1}.

Using the scheme described above, a 10-hour pumping simulation was conducted, as recovery measures were not available. The last three items of data were removed because they were taken after increasing the flow by about 10 l/s (100 l/s to 112 l/s) during the last two hours' pumping. The adjustment is shown in Figure 4, where the progressive decrease of calculated drawdowns has a maximum gradient higher than the observed one. The calibration displays certain deficiencies at the early stages of pumping, which can be put down to the switching on of the pump. The calibration errors were ME=1.2 m and MAE=1.8 m.

Various simulation times were analysed, revealing less confinement of the salty aquifer, which causes upward vertical fluxes and gravity flows. The particular situation of this test and its constructive characteristics leads us to hypothesise a mixing of the salty and fresh aquifers, thus blending their chemical properties.

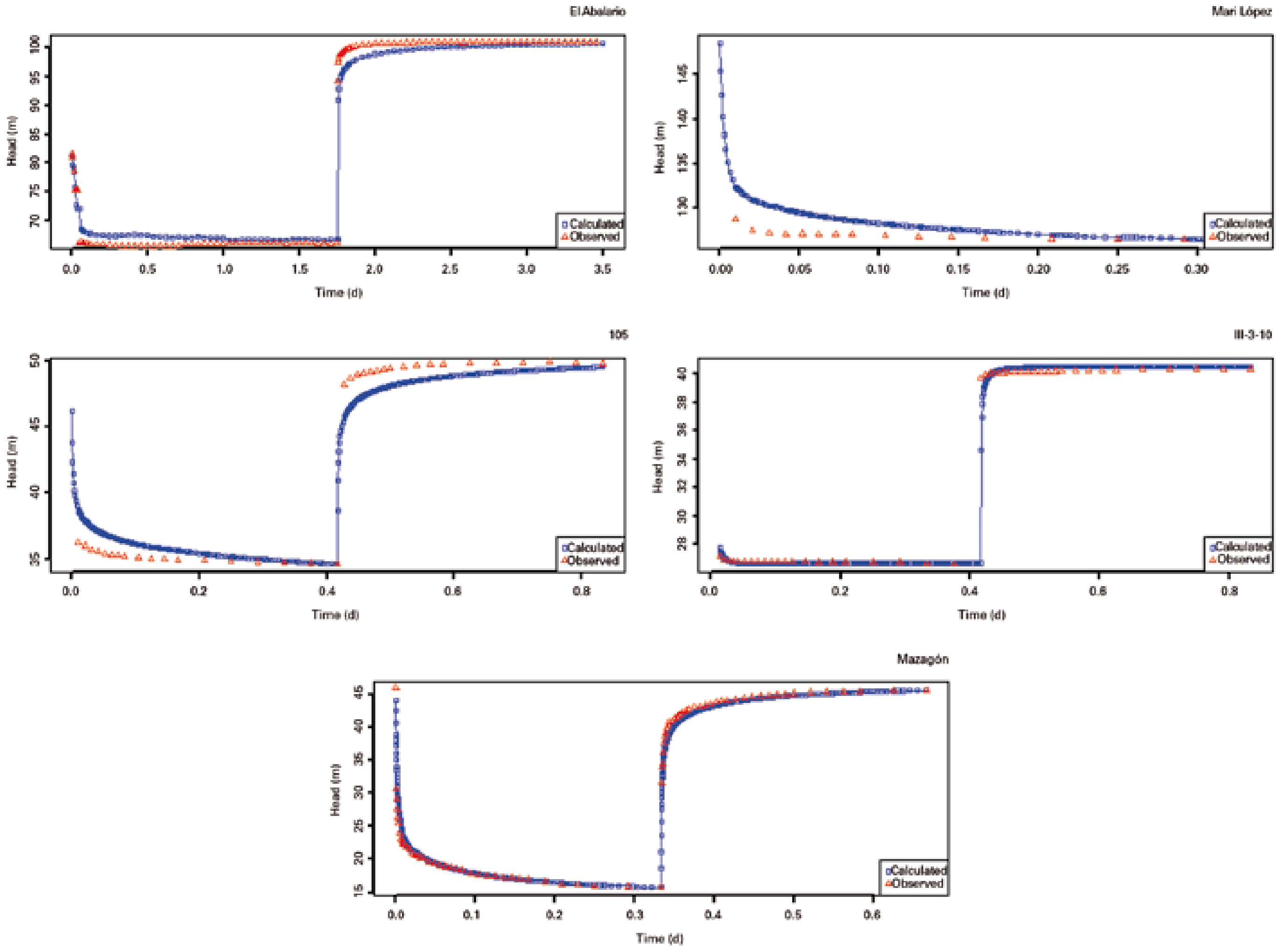

Figure 4. Best fittings for the values in Figure 3.
Figura 4. *Mejores ajustes para los valores de la figura 3.*

Whilst analysing different modelling time steps it could be seen that there were small upward vertical flows due to confinement, such as those occurring in the gravel layer when pumping stopped and at the beginning of pumping in the lower section. These small upward flows were probably a reflection of what happens during the stationary regime. The simulation showed that during pumping the gravel layer, which according to Salvany *et al.* (2001) becomes part of the Guadiamar alluvial, is the most productive section ($K_{x,y}$ = 62 m/d) and receives water from higher levels. Once the pumping test was completed the inertia forces resulted in the water regime following the direction of pumping. In remote areas the natural regime was restored sooner and the stationary regime gradually recovered. After 10 hours without pumping the well recovered completely and continued to receive flow from the gravel level and also from higher areas.

	ME	MAE	Aquifer Behaviour	Well Depth (m)	Total Filter Lengths (m)	Number of Filters
Abalario	–0.48	1.6	Unconf.	103	20	4
Mazagón	0.1	0.89	Unconf.	75	12	1
III-3-10	–0.16	0.41	Unconf.	52	26	1
MariLópez	1.2	1.8	Conf.	159	31	2
I-6-5	–0.1	1.2	Conf.	58	14	3

Table 1. ME (mean error) and MAE (mean absolute error) obtained for the simulations and some technical characteristics of the wells.
Tabla 1. *ME y MAE obtenidos para las simulaciones y algunas características técnicas de los pozos.*

Table 1 contains the ME and MAE values for each simulation as well as some physical features of the wells that might influence the results. Looking into the MAE values between 0.41 m and 1.8 m, the best fittings derive, in order of reliability, from the pumping tests carried out in III-3-10, Mazagón, I-6-5, Abalario and Mari López. The highest MAE values were obtained for the two confined wells (Mari Lopez and I-6-5) and for one of the unconfined ones (El Abalario). Assuming that the models are realistic and represent the basic functioning of the groundwater flow, the influence of the construction of the well upon the results of simulations must be emphasised: the simpler the well the better the parameters.

Discussion

The results of applying numerical modelling at various hydrogeological locations have been compared with traditional interpretations. The success of this approach and the improved confidence level in estimated hydraulic conductivity when models more attuned to real physical characteristics are employed have been highlighted.

The pumping test was conducted by the IRYDA at the El Abalario well and the resulting report (IRYDA, 1976) contains the storage coefficient values estimated by each piezometer, as well as transmissivity values estimated both during the pumping test and recovery for every observation well using the Theis-Jacob method.

Palancar and Cantos (1996) used the Hantush model so as to take into account the semi-confinement of the aquifer in the area and applied the Hidralogic software (Hidralogic, 1989), obtaining similar hydraulic conductivities to the IRYDAs interpretation for the pumping well and one piezometer. Some years later Trick (1998) did not consider the Theis-Jacob model to be suitable since it offers multiple solutions or does not satisfy every required condition (u > 0.03). Using the MARIAJ code (Carbonell *et al.,* 1997) and assuming semi-confinement behaviour and the existence of a delayed drainage, he applied both Hantush's and Neuman's models. Trick's conclusions were that the pumping well could fit multiple solutions in both cases whilst the piezometers values obtained by Hanstush were lower, except for one, and the solutions achieved by Neuman were more similar to each other. Trick regards Neuman's solution as the best approximation, similar to the solution given by the Theis-Jacob method and supported by the Thiem method, as it can be presumed that the hydraulic gradients stabilized at the end of the pumping test. On the other hand, Hantush would not be useful because of the evolution of depletion and the variability of the values obtained for each observation well. All the results given by the different authors are summarized in Table 2.

The satisfactory fitting between the calculated and observed piezometric levels support the calibrated hydraulic conductivity values with the numerical model, as well as the similarity with the values obtained by other methods. Nevertheless, the impossibility of using drawdowns in the piezometers to estimate the storage coefficient is an inherent disadvantage to the method used here. Consequently, the only parameter compared with the other methods was the hydraulic conductivity deduced from the pumping well test. Manual and automatic adjustments of drawdown curves give K = 3.1 m/d and K = 1.4 m/d respectively. Numerical modelling using MODFLOW arrives at different values for each lithology (Table 2). The gravel level is the one for which hydraulic conductivity comes closest to the estimations made with classical methods, it being the most productive level. The El Abalario pumping well is equipped with three filters, two extracting water

Method/ Software	Model	Author		Pumping Well	P1	P2	P3
Manual	Theis-Jacob	IRYDA (1976)		K_{pump} = 1.4 $K_{recovery}$ = 3.1			
Hydralogic	Hantush	Palancar and Cantos (1996)		K = 1.4	3.8	5.7	9.1
MariaJ	Hantush	Trick (1998)			2.7	4.9	6.9
AquiferTest	Neuman	Trick (1998)			4.1	3.9	5
MODFLOW	numerical	present work	Sand	$K_{x.y}$ = 0.1 K_z = 0.1			
			Fine Sand	$K_{x.y}$ = 4 10^{-3} K_z = 10^{-4}			
			Gravel	$K_{x.y}$ = 2.84 K_z = 2.84			

Table 2. Summary of results using different methods in the El Abalario pumping test.
Tabla 2. *Resumen de los resultados obtenidos por diferentes métodos en el ensayo de bombeo de El Abalario.*

from the upper layer and one from the more permeable gravel layer below it. Therefore the hydraulic conductivities obtained from analytical formulas refer to the total filter length (30 m) whilst the one obtained using MODFLOW refers to just the lower layer (10 m long), and the hydraulic conductivities representing the rest of the filtered stretches could be considered hydrogeologically negligible because of their low calibrated values.

In this case, in which the aquifer's dynamics are semi-confined, the numerical predictions of hydraulic conductivity for the most permeable layer are quite similar to the ones obtained with analytical formulas. A better representation of the total hydrogeological characteristics of the aquifer is obtained by numerical models because the less permeable upper layer is also modelled.

Mazagón: From the point of view of construction and lithological distribution this is the simplest well reanalysed in this work and its simplicity is reflected in the homogeneity of the hydraulic conductivity values obtained by every method used (Table 3). In this case, having just one filter leads to an easier simulation and is somewhat closer to the constraints related to analytical methods. In the same way, the initial assumptions of analytical methods are more likely to occur, namely the vertical flow attached to the filter edges. The two-layer numerical model's best result ($K_{x,y}$ = 8.23 m/d) is similar to that obtained using Hantush in the automatic adjustment ($K_{x,y}$ = 9.75 m/d). The confinement imposed in the three-layer numerical model ($K_{x,y}$ = 13 m/d) leads to a closer value to the Theis solution ($K_{x,y}$ = 12.08 m/d), when applying either manual or automatic adjustment (IGME, 2009). Nevertheless, the outranged storage coefficient values (10^{-6}-10^{-7}) adjusted in the three-layer model make little sense and so the two-layer model and the existence of semi-confinement are taken to be a more realistic approximation.

Model	K (m/d)
Manual graphical method: pumping	11.60
Manual graphical method: recovery	14.90
Automatic adjustment Theis	12.08
Automatic adjustment Hantush	9.75
3-layer numerical model	13.00
2-layer numerical model	8.23

Table 3. Summary of results obtained using different methods in the Mazagón pumping test.

Tabla 3*. Resumen de los resultados obtenidos con distintos métodos en el ensayo de bombeo de Mazagón.*

As with the El Abalario well, the numerical model results in higher hydraulic conductivity estimations, very similar to the ones obtained using other estimation methods. The great advantage of using numerical models, however, is that it is possible to check conceptual hypothesis. Thus, for this pumping test it was possible to corroborate a semi-confined behaviour for the less permeable layer and to conclude that the clay layer plays no important hydrogeological role, as this produces unrealistic results.

III-3-10: Both the single- and two-layer models give similar hydraulic conductivity values for the most permeable layer. These values are close to those obtained by automatic curve adjustment according to the Hantush model. In any case, the observed piezometric levels are better fitted with the single-layer model. Initial interpretations with the manual graphical method (IRYDA, 1976) are close to the ones using either the Neuman or Theis model with automatic curve software (IGME, 2009) (Table 4). Among all the reinterpretations made the numerical model ends up with the lowest values and is similar to those obtained with the Hantush model. Thus it would seem to be appropriate to consider that the behaviour of the aquifer in this area may be semi-confined by the clay level and receive a water supply from the top section. Hydraulic conductivity values obtained with the manual graphic method and with the Theis or Neuman models seem to be overestimated. Furthermore, other nearby pumping-tests result in similar hydraulic conductivity values of over 10-20 m/d (IRYDA, 1976).

Manual		K = 188 m/d
Automatic	Hantush	K = 37 m/d
	Neuman- pumping	K = 167 m/d
	Neuman-pumping and recovery	K = 91 m/d
MODFLOW		K = 28.3 m/d

Table 4. Summary of results using different methods in the III-3-10 pumping test.

Tabla 4*. Resumen de los resultados por distintos métodos en el ensayo de bombeo III-3-10.*

Mari López: In the light of the different interpretations made for the Mari López pumping test, situated in a confined area of the aquifer, the estimated hydraulic conductivity using the numerical modelling is lower than that deriving from the results obtained manually from the curve-adjustment method (IRYDA, 1976) or with automatic software (IGME, 2009), as is reflected in Table 5. Deviations in the hydraulic conductivity values, with various interpretations, are significant and can be explained by the characteristics of the pumping test and the environment of its location, Assumptions related to the application of analytical equations are not met: the well presents several stretches of filters at different depths; the medium is heterogeneous; the well radius is not zero; and the extraction flow is not constant, showing that the associated error sometimes cannot be considered negligible. Therefore the modelling estimations can be considered to be more reliable since the different lithologies are taken into account in the simulation. On the other hand, it is interesting to highlight the fact that small $K_{x,y}$ values assigned to the clays strongly influence and pose very strict conditions upon the water flow.

Manual Graphical Method	K = 57 m/d
Automatic Curve Method	K = 37 m/d
MODFLOW	$K_{x,y}$ = 14 m/d

Table 5. Summary of results using different methods in the Mari López pumping test.
Tabla 5*. Resumen de los resultados en Mari López por distintos métodos.*

I-6-5: This point is also located in the confined part of the aquifer. Table 6 summarizes the values obtained via the different interpretation methods. The manual adjustment of the graphic method (IRYDA, 1976) estimates hydraulic conductivity to be 80 m/d, whilst automatic curve adjustment (IGME, 2009) results in 70 m/d. Numerical modelling provides different values of $K_{x,y}$ for each of the modelled layers, giving smaller $K_{x,y}$ than the other methods. Thus it can be seen that in the area of the aquifer with confined behaviour the hydraulic conductivity values obtained by classical methods, as with Theis-Jacob, are overestimated. It is also important to note that the numerical model can differentiate between lithologies and the filter placement, which are reflected in the simulated flow distribution. In any case, the differences between the results of the most permeable layer obtained by different methods are not as significant as in the case of Mari López. Both I-6-5 and Mari López, reflect the high hydraulic conductivity values found in marshland wells.

Manual Graphical Method	K = 80 m/d		
Automatic Curve Method	K = 70 m/d		
MODFLOW	Marl	$K_{x,y}$ = 0.095	K_z = 0.001
	Sand	$K_{x,y}$ = 6	K_z = 1.55
	Gravel	$K_{x,y}$ = 62	K_z = 23.3

Table 6. Summary of results using different methods in the I-6-5 pumping test. (K in m/d).
Tabla 6*. Resumen de los resultados en I-6-5 por distintos métodos.* (K en m/d).

Conclusions

Numerical simulations of two-dimensional models representing a pumping well are shown to be suitable for reproducing groundwater flow during the test and estimating hydraulic conductivity, differentiating between lithologies and filter placements. The possibility of separating both vertical and horizontal hydraulic conductivity values for each layer allows us to simulate both horizontal and vertical flows. The great advantage of using numerical models is that it is possible to check conceptual hypotheses. Thus it has been possible to corroborate semi-confined behaviour and take into account unrealistic results. Among all the reinterpretations made in the five pumping tests the reanalysed numerical model ends up with the lowest values for conductivity (Tables 1 to 5). Thus, it would seem that in the area of the aquifer with confined behaviour, classical methods, such as the Theis-Jacob approach, tend to overestimate hydraulic conductivity values. Semi-confined or confined dynamics, which can be reproduced by classical methods only with difficulty, can be simulated with the method applied here. The Mari López pumping test shows the importance of K_z in both permeable and impermeable layers. Where the dynamics of the aquifer are semi-confined, a better representation of the total hydrogeological characteristics of the aquifer is obtained by numerical models than it is when a less permeable upper layer and vertical hydraulic conductivities are involved.

The quality of the results varies, however, depending upon such factors as the complexity of the deep lithological distribution and subsequent complexity of the well design, as shown in the examples presented here. Thus, in the Mazagón well the result is more reliable since it is equipped with just one filter. Another drawback is the impossibility of using drawdowns in the piezometers and consequently of estimating the storage coefficient, which is an inherent disadvantage of the method.

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