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The problems of overexploitation of aquifers in semi-arid areas: the Murcia Region and the Segura Basin (South-east Spain) case

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The problems of overexploitation of aquifers in semi-arid areas

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Abstract

A general analysis of the problems arising from aquifer exploitation in semi-arid areas such as the Autonomous Region of Murcia, which belongs to the Segura Basin is presented, with particular reference to the Ascoy-Sopalmo aquifer, which is the most overexploited aquifer in Spain. It has suffered intense overabstraction over the last forty years, given renewable water resources of $2\,Mm^3\,yr^{-1}$ and abstractions amounting to as much as $55\,Mm^3\,yr^{-1}$. This has resulted in the drying of springs, continuous drawdown of water levels ($5\,m\,yr^{-1}$); piezometric drops (over 30 m in one year, as a consequence of it being a karstic aquifer); increase in pumping costs (elevating water from more than 320 m depth); abandoning of wells (45 reduced to 20), diminishing groundwater reserves, and deteriorating water quality (progressing from a mixed sodium bicarbonate-chloride facies to a sodium chloride one). This is a prime example of poor management with disastrous consequences. In this sense, a series of internal measures is proposed to alleviate the overexploitation of this aquifer and of the Segura Basin, with the aim of contributing to a sustainable future.

1 Introduction

Since 1989, when the conference "Overexploitation of aquifers" was held in Almería, and since 1991 (two years later), when the 13th International Conference of the IAH was dedicated to "Aquifers Overexploitation" (in both conferences the author presented several articles), a vast number of researchers have shown interest on this matter (Custodio, 1989; Pulido et al., 1989, 2002; Simmers et al., 1991; Rodríguez-Estrella, 2004; Petit, 2004: Hani et al., 2006; Bajjali et al., 2006; Hsu et al., 2007; Serrat et al., 2007; Ibáñez et al., 2008; Closson et al., 2009; Molina et al., 2009, 2010, 2011; Wu et al., 2009; Praveena et al., 2010; Van Camp et al., 2010; Qureshi et al., 2010; Ali et al., 2011).

The Autonomous Region of Murcia, in South-Eastern Spain and belonging to the Segura Basin, is one of the most arid European regions (in the coast, rainfall is of 300 mm, and temperature reaches 18° in average) as well as one of the worst-affected by degree of groundwater overexploitation. With an inflow of water resources of 358 $Mm^3 yr^{-1}$ (307 $Mm^3 yr^{-1}$ from rainfall and 51 $Mm^3 yr^{-1}$ to irrigation returns), the outflows total 520 $Mm^3 yr^{-1}$, or one and a half times the inflow (of which 140 $Mm^3 yr^{-1}$ correspond to natural spring flow and the remaining 380 $Mm^3 yr^{-1}$ to pumped abstractions). Thus, there is a water deficit of 162 $Mm^3 yr^{-1}$. Nevertheless, the total overabstraction summed over all the aquifers is 214 $Mm^3 yr^{-1}$. This hydrologic balance of the Murcia Region (Rodríguez-Estrella, 2004) corresponds to the year 1995 (dry year).

In Fig. 1, the situation of both the Region of Murcia and the Ascoy-Sopalmo aquifer can be observed within Spain and Europe, and Fig. 2 shows the map of overexploitation of aquifers in the Region of Murcia.

Geographically, the imbalance in Murcia is most intense in the east of the Region, where climatic conditions are the most favourable for developing modern agriculture, for which the largest groundwater abstractions are made.

Of all Spanish aquifers, the Ascoy-Sopalmo aquifer (3 in Fig. 2) suffers the most extreme overexploitation and the greatest problems stemming from: continued drawdown of water levels, increasing pumping costs, abandonment of wells, diminishing groundwater reserves, compartmentalization, change in physical characteristics (thermalism) and chemical water quality, as well as drying up of springs. As a result, it merits special attention.

2 Concepts of aquifer overexploitation and sustainable management

2.1 Aquifer overexploitation

The concept of overexploitation has varied along time, from the failed attempt of definition given in Pulido (1989) to the first successful one – although somehow euphemistic

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– in which overexploitation is defined as "that exploitation which produces undesired effects" (Candela et al., 1991; Simmers et al., 1992).

Recently, many authors and organizations have investigated this topic, in such works as (Gleeson, 2010; Molina et al., 2009, 2010, 2011; Malik et al., 2004; UNESCO COMEST, 2003; Qureshi et al., 2010; Ali et al., 2011).

Therefore, from the definition given by Pulido (2001), we can say that overexploitation is produced when the quantity of water extracted from an aquifer is much greater (more than double) than its pluriannual recharge and this produces negative impacts in the physical and biotic environments; all this referring to a sufficiently long period (25 years for South-Eastern Spain), with the aim of being able to distinguish it from a period of drought (4 to 5 years), in such a way that it is practically impossible to re-establish the original state of equilibrium. Its essential differentiating characteristic is a continuous fall in piezometric level (Rodríguez-Estrella, 2004).

Over the last twenty years, some authors have been completely against using the term "overexploitation" because of its implied negative connotation, and propose instead, the term *intensive use* (Custodio, 1989).

2.2 Sustainable management

Groundwater sustainability is understood, in accordance with the definition given by circular 1186 published by the United States Geological Service (Sustainability of Ground-Water Resources- USGS, 1998) as "the development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic or social consequences".

To achieve sustainable management of groundwaters, the USGS proposes the following strategies:

a. Use sources of water other than local groundwater, for example, importing surface water from outside river catchements that are in surplus.

b. Change rates or spatial patterns of groundwater pumping.

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c. Increase recharge to the groundwater system.

d. Decrease discharge from the groundwater system.

e. Change the volume of groundwater in storage at different time scales.

As we shall see, achieving sustainability for an aquifer that is in such an advanced state of deterioration as Ascoy-Sopalmo will not be easy.

3 Effects of aquifer overexploitation

In many cases, intensive aquifer exploitation includes an initial phase that has positive effects but, over time, the effects usually become negative as it turns into overexploitation. This subject receives full discussion by Rodríguez-Estrella (2004), with only the most important points being stated here.

3.1 Positive effects of intensive exploitation

Progressive economic development. (Aragón et al., 1992). Infrastructure benefits (water pipes, roads, electricity supplies, etc.). Re-infiltration of excess irrigation water with recharge of the aquifer, when the abstracted water is applied to the same, permeable terrain. – Recovery of saline soils (as there is more water, there is greater solution). Increase in vegetation cover, which improves rainfall infiltration. Change from a non-irrigated to an irrigated regime, with all the concomitant economic benefits.

3.2 Negative impacts of overexploitation

3.2.1 Direct

Continuous fall in piezometric levels; of up to $10\,\mathrm{m\,yr^{-1}}$, as in the aquifer of Don Gonzalo-La Umbría – 6 in Fig. 2 – (Andreu et al., 2004). Increase in the economic cost of pumping; in the Triassic aquifer "Las Victorias" (7 in Fig. 2), the piezometric level now lies below 500 m. Abandonment of wells; in 1971 in the Ascoy Sopalmo aquifer, focus of this article, there were 146 production wells; by 1987, only 60 were still active, and now (2010) there are fewer than 20. Diminishing groundwater reserves. Induced compaction of the land surface and appearance or accentuation of endorrheic or semi-endorrheic areas. Compartmentalization of aquifers; apart from the Ascoy-Sopalmo aquifer, the Quibas aquifer went from a single compartment to seven between 1973 and 1980 (Rodríguez-Estrella, 2004). Change in the physical and chemical characteristics of the groundwater; hand in hand with the overexploitation, the groundwater abstracted sometimes becomes thermal and their chemical facies change, for example, going from bicarbonate to sulphate facies, or vice verse. Modification induced in the river flow regime. Impact or desiccation of wetlands and springs (López Bermúdez et al., 1988). Changes in the groundwater extraction systems.

3.2.2 Indirect

Land subsidence and collapse, giving rise to geotechnical impacts in dwellings (Cooper, 1998). Pipeline breakages and deterioration of road surfaces. Salinization of soils. Progressive desertification (Martínez-Mena, et al., 2001). Modification or suppression of flora; change from phreatophytes to xerophytes. Disappearance of a particular fauna and substitution by another (Rodríguez-Estrella and López Bermúdez, 1992). Abandonment of agriculture and emigration from towns and villages. Decline or disappearance of sheep herds. Decline of hunting and angling. Cessation of wetlands resource exploitation. Change in landscape and lack of correlation with ancient place names. Alteration of the physical properties of the aquifer water. Creation of depression cones that mobilize pollutants from remote areas. Modification of the local climate (wetland areas moderate climate). Sea level rise in the Mediterranean. Legal problems from impacts on water abstraction points. Negative social, economic and political impacts. Disappearance or deterioration in landscape features or hydrological and

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hydrogeological features that formed part of the national heritage (Rodríguez-Estrella, 1999).

4 The Ascoy-Sopalmo aquifer

4.1 General characteristics of the Ascoy-Sopalmo aquifer before division

1. It belongs to the municipalities of Jumilla and Cieza, with a smaller portion in Abarán, all in the region of Murcia; a tiny part in its south-eastern corner falls into Alicante province (Fig. 1).

2. Geologically, the aquifer is situated in the Betic Cordilleras, in the Prebetic Zone and specifically in the palaeographic domain of the Southern Prebetic. The main permeable rock comprises an average of 350 m Upper Cretaceous dolomites and Palaeocene limestones, with Lower Cretaceous marls forming its impermeable base. In the Carche sector, these are overlain by two further permeable rock layers that are hydrogeologically independent: 125 m Middle Eocene limestones and 200 m Lower Miocene calcarenites; these last two aquifer layers are of only local importance and will not be referred to further.

3. With respect to the aquifer's geometry, there are three structural elements, which are, from west to east:

   - The western sector is defined by a central anticlinal-horst.
   - The central part of the aquifer is a northward thrust fault south of the Sierra Larga.
   - The eastern part is formed by north-thrusting mushroom folds.

4. The hydrogeological limits are as follows:

   - To the north, by the outcrops of the impermeable base.

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- To the east, by a series of faults deduced from geophysics.
- To the south and southeast, the thrust fault of the Sierra of the Pila-Cerros de Solsía places.
- To the west, the Cieza tear fault and the thrust fault of Sierra Larga.

Defined thus, the aquifer covers a surface area of 426 km^2.

5. Until 1969 natural spring flows were recorded in Fuente del Ojo and Zaraiche el Mayor; these waters were used to supply traditional irrigation rights ("heredamientos") in the vicinity of Cieza.

6. The elevated exploitation, 55 $Mm^3 yr^{-1}$ compared to a 2 $Mm^3 yr^{-1}$ recharge (the last-mentioned figure being deduced from flow records of the springs emerging from the aquifer in the days before pumped abstractions) provoked the direct negative impacts outlined above.

7. The water-level contour map for March 1986 and performed with data extracted from 60 boreholes existing at that time – shows the borders of the aquifer as defined at that time (Fig. 3). One can notice that the generalized groundwater flow in the aquifer is from NE to SW. However, the water-level contour curves are heavily distorted by the effect of pumping, which was at a peak at this time; the piezometric level lay between 250 m a.s.l. in the NE, and 160 m a.s.l. in the SW. Figure 3 also shows a piezometric map for the spring of 1991 and, given that exploitation had diminished by this time, the curves are seen to be less distorted. The piezometric levels go from 140 m a.s.l. in the SW, to 190 m a.s.l. in the N.

8. The state of overexploitation caused continuous drops in water level in the boreholes. Between 1970 and 1994, there was a prolonged drop of the piezometric level of some 5.5 $m yr^{-1}$.

9. In March 1986, salinity ranged from 1100 and 1500 $mg l^{-1}$ and the aquifers water had changed from a mixed sodium chloride-bicarbonate facies (1972) to a sodium

chloride one (in 1986) due to the influence of the Triassic deposits along the aquifer's north-eastern and south-western borders in the face of the overexploitation.

10. Transmissivities generally exceed 500 $m^2 day^{-1}$, with up to 2500 $m^2 day^{-1}$ being recorded in the new, deep wells; the latter result indicates that karstification is well-developed at depths of between 500 and 700 m.

11. Water reserves for 1991 were estimated to be 3500 Mm^3 (IGME, 1993, unpublished). These reseerves were calculated using the graphical method devised by Solís et al. (1983), based on making numerous hydrogeological cross-sections and height contour maps of the sides and top of the main permeable rock.

Over the period 1970–2009 (39 yr), exploitation of the water reserves were calculated to be 1600 Mm^3; accordingly, by 2009 only 1900 Mm^3 remained, giving a maximum life at today's rate of exploitation of only 40 yr; this window could be even shorter given that the depth of the water, its poor quality and high abstraction costs will curtail the phase of exploitation. Were there a desire to return the aquifer to its original state, it would take 800 yr.

4.2 Analysis of the excision of the Ascoy-Sopalmo aquifer

The latest investigations undertaken by the author in the extreme south-west of the aquifer, using geophysics in deep boreholes, highlight that the main aquifer (the permeable rock of the Upper Cretaceous) has split into four hydrogeological compartments or subaquifers, since 2004 (although it may have begun in during 1994). Have been denominated: Ascoy, Benís, Sierra Larga and Sopalmo-Carche (Fig. 4).

Figure 5 indicates the hydrogeological independence along the section I-I'.

Figure 6 shows the water-level contour lines corresponding to 24 November 2004, in the Ascoy, Benís and Sierra Larga compartments, and the number of boreholes.

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In the *Ascoy subaquifer* the groundwater flow is generally towards the SW, with a gradient of 1 %, (towards the former spring of Fuente del Ojo). Nowadays, the flow follows this path because the only wells being exploited are to the north of Cieza where the topography is less pronounced. The majority of the boreholes in this Sierra and shown on Fig. 6 are dry, since they are situated on mountain slopes, the piezometric level has fallen to the impermeable base. By the end of 2004, the piezometric level lay between 162.66 m a.s.l., in well 3, and 116.42 m a.s.l., in the "Zaraiche II" well. On 27 February 2007, the water level in "Jesús II" was at 156.3 m (107 m a.s.l.). Nevertheless, when the Jesús II ($Q = 90\,\mathrm{l\,s^{-1}}$) was brought into production in 2005, water levels began to fall again at a rate of $4.4\,\mathrm{m\,yr^{-1}}$, as seen from Fig. 7, which shows piezometer 2, of the CHS.

In the *Benis subaquifer*, groundwater flow is southwards, as in Ascoy, but here the gradient is 4.5 %. The Chopo borehole (60 m a.s.l. in 2004) produced a piezometric drop of 30 m (the water level fell from 269.4 to 300 m deep) between 24 November 2004 and 13 January 2006. On 10 November 2009, the level was 18 m a.s.l. (depth of water table was 320 m).

In the *Sierra Larga aquifer* the piezometric level lay, in the Sierra Larga I (SL-I) borehole at 131.54 m a.s.l. at the end of 2004, and by 6 August 2008, it lay at 115.27 m a.s.l.; indicating a drop of 14.27 m in under four years ($4\,\mathrm{m\,yr^{-1}}$).

The *Sopalmo-Carche subaquifer* has no up-to-date data. However, according to the piezometric network monitored by the CHS, piezometer 5 showed a fall in level of $5.8\,\mathrm{m\,yr^{-1}}$ between 2005 and 2009, when it lay at 51.8 m a.s.l.

4.3 Chemical quality and thermalism

In 1972, the chemical facies of all the waters in the Ascoy-Sopalmo aquifer was mixed sodium chloride-bicarbonate; even in the Sierra Larga it was still sodium-calcium bicarbonate-chloride. For example in the Fuente del Peral borehole, when the water level was at a depth of 100 m, the residual solids were $686\,\mathrm{mg\,l^{-1}}$, bicarbonates, $262\,\mathrm{mg\,l^{-1}}$, chlorides, $178\,\mathrm{mg\,l^{-1}}$, sodium was $92\,\mathrm{mg\,l^{-1}}$ and calcium, $82\,\mathrm{mg\,l^{-1}}$.

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However, since 1986, as a consequence of overexploitation, all the water has taken on a sodium-chloride facies, although the salinity was not elevated at this stage (in March 1986, salinity was 1500 mg l^{-1}, chlorides, 680 mg l^{-1}, sodium was 300 mg l^{-1}). This is due to saline intrusion over the northern and south-western limits of the aquifer (where Triassic evaporites are present), drawn in by the intensive pumping from the aquifer.

Table 1 presents the temperature data and most important chemical characteristics for certain boreholes in the Ascoy and Sierra Larga subaquifers in recent times. The Roman numeral I corresponds to the investigation borehole, and II with the production well.

From Table 1, the following can be deduced:

1. Conductivity increases with depth.

2. Temperature generally increases with depth (Fig. 8).

3. Conductivity and temperature are linked: the higher the temperature, the greater the solubility and the salinity.

4. Other factors also intervene, such as the type of aquifer in question. In general, for a given depth, water taken from a confined aquifer will show higher temperatures than water from a free aquifer. The reason is that in the confined aquifer, the impermeable confining strata act as an insulator and the groundwater flow is horizontal, while in a free aquifer, where the permeable rock outcrops on the ground surface, the heat is more easily dispersed, since the flow is vertical.

5 Proposal of internal actions to alleviate the hydric deficit of the Segura Basin

There is no doubt that the high deficit in the Segura Basin can only be sorted out with the spare water coming from the Ebro River, which is of good chemical quality (i.e. the water going to the sea, more than 10 000 $Mm^3 yr^{-1}$). However, until it gets here (there

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was an attempt in 2004 but the project was stopped), a series of internal actions can be carried out, such as Rodríguez Estrella (2004) and Molina et al. (2009):

Combined use of subterranean waters with surface river waters. Combined use of subterranean and superficial reservoir waters. Inter-basin water transfer. Global hydric Education, free from patriotic chauvinism. Optimization of natural resources, by means of karstic spring regulation. Extraction of part of the reserves in deep unexploited aquifers. Space redistribution of the extractions. Use of waters from rises. Constitution of the Communities of Users of the aquifers and design of the Management Plans of the overexploited. Adapting of the chemical quality of the water to its final use. Installing of more efficient irrigation systems. Agricultural transformation. Use of residual waters for irrigation, once depurated. Desalination of salty and sea waters through coastal aquifers (Rodríguez-Estrella and Pulido, 2009). Computerizing of irrigation surfaces, conductions and water applications.

6 Consideration of actions that would contribute to the sustainable management of the Ascoy-Sopalmo aquifer

The Ascoy-Sopalmo was officially declared overexploited on 7 January 1987 and, although this declaration included a Plan for the Regulation of Water Use (PRWU), the latter was never executed, due to disagreements amongst the water users. These PRWU are hindered by legal questions, more than by technical or financial concerns.

Since Spain's legislation allows groundwater to be both publicly and privately owned, one of the principal difficulties is rooted in the constitution of the Water Users' Communities (WUC), generally competing interests. The Ascoy–Sopalmo WUC was formed in 2006.

In terms of the basic or general actions involved in the PRWU, and which will have to be undertaken for the Ascoy-Sopalmo aquifer, the following are highlighted:

1. Approval of the perimeter of the groundwater protection zone.

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2. Establishment of a network of monitoring piezometers and others for water quality – the Segura Hydrographic Confederation (CHS) – has already established monitoring points in all its groundwater bodies.

3. A standard abstraction will be defined to limit both the volumes of the water concessions to be made to aquifer users, and the implementation of options to release part or all of the flow allocated to each user. Flow gauges will be installed at every abstraction point in order to effectively monitor the quantity of water taken.

4. With the exception of investigations undertaken by the Competent Water Administration, there is an absolute ban on test drillings to determine groundwater availability within the groundwater protection zone.

5. Reorganization of aquifer abstractions. These reorganizations will have to be approved by the Water Resource Coordinators of the aquifer.

6. Delimitation of the irrigation zone.

The complexity of the matter clearly requires that the solutions are articulated in the River Basin Hydrological Plans (RBHPs); however, since to date there is still no PRWU, no provisions are laid down that can be incorporated in the future RBHPs. In addition, the terms of the Water Framework Directive (WFD) stipulated that these plans had to completed by December 2009, and so the process is already behind schedule.

So, compliance of the overexploited aquifers with the environmental objectives of the WFD (for 2015), necessarily requires the incorporation and replacement of groundwater abstractions using external surface water. However, given the high degree of overexploitation of some aquifers like Ascoy-Sopalmo, there will need to be an application for extensions (there will be two extensions of six years, until 2027) and, predictably, a request to derogate certain environmental objectives and set less stringent goals. The WFD envisages derogation of environmental objectives for groundwater bodies that are seriously (or irreversibly) deteriorated or whose recovery would entail disproportionate costs, but it also lays down that the deterioration should not continue.

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7 Conclusions

1. Whilst the initial phase of aquifer overexploitation in the Segura Basin brought positive effects but the greatest impacts of the overexploitation have been negative, both directly and indirectly.

2. With the aim of alleviating the hydric deficit that the Segura Basin suffers (460 $Mm^3 yr^{-1}$), and while part of the waters from the Ebro River going to the sea arrives (10 000 $Mm^3 yr^{-1}$), a series of internal actions can be carried out within the Basin, such as: combined use of subterranean waters with surface river waters; combined use of subterranean and superficial reservoir waters; inter-basin water transfer; global hydric education, free from patriotic chauvinism; optimizing of natural resources, by means of spring regulation; extraction of part of the reserves in deep unexploited aquifers; space redistribution of the extractions; use of waters from swellings; constitution of the Communities of Users of the aquifers and design of the Management Plans of the overexploited; adapting of the chemical quality of the water to the final use; installing of more efficient irrigation systems; agricultural transformation; use of residual waters for irrigation, once depurated; desalination of salty and sea waters through coastal aquifers; computerizing of irrigation surfaces, conductions and water applications.

3. Many of the negative impacts mentioned have occurred in the Ascoy-Sopalmo aquifer, the most-heavily overexploited aquifer in Spain, and very probably in Europe. The size of the negative water balance over forty years (55 $Mm^3 yr^{-1}$ extracted against a renewable resource of only 2 $Mm^3 yr^{-1}$) has caused: drying out of springs, continuous fall in piezometric levels (5 $m yr^{-1}$); drops in piezometric level (more than 30 m in a single year since it is a karstic aquifer), increase in the economic cost of elevation (water lies at more than 320 m depth); abandonment of wells (from 45 to 20), diminishing groundwater reserves, deterioration in chemical water quality (change from a mixed sodium chloride-bicarbonate facies to sodium chloride) and, above all, division of the aquifer into four independent subaquifers.

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It is estimated that over the period 1970–2009 (39 yr), exploitation of reserves amounted to 1600 Mm^3; according to these calculations, by 2009 only 1900 Mm^3 remain, giving a maximum productive life of 40 yr at the current rate of abstraction; this period could be even shorter since the poor water quality and the costs associated with drawing it from such depth will curtail the exploitation phase further. If the aquifer were to be recovered to its original state, it would take around 800 yr.

4. The proposals required to bring the Ascoy-Spolamo aquifer back to a sustainable state are as follows:

   a. Drawing up of a Water Use Regulation Plan for the aquifer; the Plan was initiated in 2007, but has not been complete due to legal questions. The Plan should include:

      - Approval of the perimeter of groundwater protection zone.
      - Establishment of a monitoring network for water level and water quality.
      - Establishment of the volumes of water concessions made to each aquifer user, and the implementation of options for releasing part or all the allocated flows.
      - Absolute ban on the sinking of new boreholes within the delimited protection zone.
      - Reorganization of aquifer abstractions.
      - Delimitation of the zone where crop irrigation is allowed.

   b. Given that the Segura Basin, and specifically the Ascoy-Sopalmo aquifer hold insufficient resources to meet demand, water transfers from other catchment are required (specifically from the Ebro) to substitute for water currently extracted from the overexploited aquifers.

   c. In the case of sorting out and reorganizing abstractions from inland aquifers, as in our case, it is proposed that the sources are permuted, taking advantage of the new water resources issuing from the coastal desalination plants to

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meet concessions near to the coast, and reallocating their concessions of upstream water to supply the users of the inland aquifers.

d. In the Jumilla-Villena and Ascoy-Sopalmo aquifers (Comarca del Altiplano), reallocation of resources is proposed whereby the towns of Jumilla and Yecla, (which currently take groundwater from the two overexploited aquifers referred to), would be supplied from surface water deriving from the the Canales del Taibilla Water Users's Community, be means of the Cenajo Reservoir transfer scheme.

e. The Vinalopo and Alicante Coastal districts, which are also supplied from these two aquifers, will have the possibility of new resources arising due to reallocation of desalinated water and the Júcar-Vinalopó water transfer scheme, both contributing to reorganization of water concessions.

5. If the overexploited aquifers are to comply with the environmental objectives of the Water Framework Directive (by 2015), it will be necessary to replace groundwater abstractions using external surface water sources. However, given the extreme degree of overexploitation of certain aquifers, like Ascoy-Sopalmo, there will be a need to request extensions (two extension each of six years are foreseen, taking the compliance date forward to 2027). It is also foreseen that a request will have to be made to set less rigorous environmental objectives. The WFD envisages derogation of environmental objectives for groundwater bodies that are seriously (or irreversibly) deteriorated or whose recovery would entail disproportionate costs, but it also lays down that the deterioration should not continue.

6. With the recent change of government in Spain (20 October 2011), to one that is more supportive of water transfer schemes than of desalination options, there is a chance for alleviating the grave situation of Spain's most overexploited aquifer.

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References

Ali, M. H., Abustan, I., Rahman, M. A., and Haque, A. A. M.: Sustainability of groundwater resources in the north-eastern region of Bangladesh, Water Resour. Manage., 26, 623–641, doi:10.1007/s11269-011-9936-5, 2011.

Andreu, J. M., Pulido, A., Rodríguez-Estrella, T., and Garcí a Sánchez, E.: Sobreexplotación de acuíferos kársticos, Capítulo del libro: Investigaciones en sistemas kársticos españoles, Public. del IGME, serie Hidrogeología and Waters Subterráneas 12, Madrid, 161–184, 2004.

Aragón, R., Solís, L., García, U., Grís, J., and Rodríguez-Estrella, T.: Groundwater problems in Segura Basin, Economic impact of overexploitation in the Mazarrón zone (Murcia, Spain), Selected Paper on Aquifer Overexploitation, AIH, 3.235-246, Hannover, 1992.

Bajjali, W. and Al-Hadidi, K: Recharge: Origin, overexploitation, and sustainability of water resources in an arid area from Azraq basin, Jordan: Case study, Nord. Hydrol., 37, 277–292, 2006.

Candela, L., Gómez, M., Puga, L., Rebollo, L., and Villarroya, F.: Aquifer overexploitation, AIH, 580, Tenerife, 1991.

Closson, D. and Abou Karaki, N.: Human-induced geological hazards along the Dead Sea coast, Environ. Geol., 58, 371–380, 2009.

Cooper, A. H.: Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigation and remediation, in: Geohazards in Engineering Geology, edited by: Maund, J. G. and Eddleston, M., Geological Society, London, 265–275, 1998.

Custodio, E.: Consideraciones sobre la sobreexplotacion de acuíferos en España, La sobreexplotación de acuíferos, AIH-AEHS, Almería, 43–64, 1989.

Gleeson, T., VanderSteen, J., Sophocleous, M. A., Taniguchi, M., Alley, W. M., Allen, D. M., and Zhou, Y. X.: Groundwater sustainability strategies, Nat. Geosci., 3, 378–379, 2010.

Hani, A., Lallahem, S., Mania, J., and Djabri, L.: On the use of finite-difference and neural-network models to evaluate the impact of underground water overexploitation, Hydrol. Process., 20, 4381–4390, 2006.

Hsu, K., Wang, C., Chen, K. C., Chen, C., and Ma, K.: Climate-induced hydrological impacts on the groundwater system of the Pingtung Plain, Taiwan, Hydrogeol. J., 15, 903–913, 2007.

Ibáñez, J., Valderrama, J. M., and Puigdefábregas, J.: Assessing overexploitation in Mediterranean aquifers using system stability condition analysis, Ecol. Model., 218, 260–266, 2008.

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López Bermúdez, F., Rodríguez-Estrella, T., Navarro, F., and Romero, A.: Zonas húmedas y sobreexplotación de los acuíferos subterráneos, El caso del Salobral (Albacete), Internat. Simp. on Hydrolog of wetlands in semi-arid and arid regions, Sevilla, 107–110, 1988.
Malik, A., Badruddin, M., Khan, M. J., Latif, M., and Haq, I.: Effect of overexploitation of ground water resources on water balance and quality in Lachi valley of district Kohat, Pakistan, Sarhad J. Agric., 20, 125–133, 2004.
Martínez-Mena, M., Castillo, V., and Albadalejo, J.: Hydrological and erosional response to natural rainfall in a degraded semi-arid area South-East Spain, Hydrol. Process., 15, 555–571, 2001.
Molina, J. L., García Arístegui, J. L., Benavente, J., Varela, C., de la Hera, A., and López-Geta, J. A.: Aquifers overexploitation in SE Spain: a proposal for the integrated analysis of water management, Water Resour. Manage., 23, 2737–2760, 2009.
Molina, J. L., Bromley, J., García-Aróstegui, J. L., Sullivan, C., and Benavente, J.: Integrated water resources management of overexploited hydrogeological systems using object-oriented bayesian networks, Environ. Model. Softw., 25, 383–397, 2010.
Molina, J., García-Aróstegui, J. L., Bromley, J., and Benavente, J.: Integrated assessment of the European WFD implementation in extremely overexploited aquifers through participatory modelling, Water Resour. Manage., 25, 3343–3370, doi:10.1007/s11269-011-9859-1, 2011.
Petit, O.: Groundwater overexploitation: stakes and governance, Natures Sci. Soc., 12, 146–156, 2004.
Praveena, S. M., Abdullah, M. H., and Aris, A. Z.: Modeling for equitable groundwater management, Int. J. Environ. Res., 4, 415–426, 2010.
Pulido, A.: Sobreexplotación de acuíferos y desarrollo sostenible. Problemática de la gestión del agua en regiones semiáridas, Inst. Est. Almerienses, Dip. Almería, Almería, 115–132, 2001.
Pulido, A., Castillo, E., and Padilla, A.: La sobreexplotación de acuíferos, AIH-AEHS, 687, Almería, 1989.
Pulido, M., Andreu, J., Sahuquillo, A., Pinilla, V., Sánchez, A., Capilla, J., and Paredes, J.: Optimization of water resources management under aquifer overexploitation conditions: the Adra – Campo de Dalías system, Spain, Water Stud., 10, 87–99, 2002.
Qureshi, A. S., McCornick, P. G., Sarwar, A., and Sharma, B. R.: Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan, Water Resour. Manage., 24, 1551–1569, 2010.

Rodríguez-Estrella, T.: Some considerations on the concept of "Hydrogeological Heritage", with special reference to the Hydrogeological Heritage of the Murcian Region of Spain, Towards the Balanced Management and Conservation of the Geological Heritage in the New Millenium, SGE, ITGE, ProGeo, Madrid, 166–172, 1999.
Rodríguez-Estrella, T.: Sobreexplotación de acuíferos y desertificación en el Sureste Español, Capítulo del Libro: Aridez, Salinizacion y Agricultura en el Sureste Ibérico, Fundación Ramón Areces y Fundación Instituto EuroMediterranean de Hidrotecnia, Madrid, 105–134, 2004.
Rodríguez-Estrella, T. and López Bermúdez, F.: Some ecological consequences of aquifer overexploitation in welands in Spain, Selected Paper on Aquifer Overexploitation, AIH, 3, Hannover, 93–107, 1992.
Rodríguez-Estrella, T. and Pulido Bosch, A.: Methodologies for abstraction from coastal aquifers for supplying desalination plant in the south-east of Spain, Desalination, 249, 1088–1098, 2009.
Serrat, P. and Lenoble, J.: Groundwater overexploitation in Roussillon floodplain: a major problem for the future, Houille Blanche, 3, 71–78, 2007.
Simmers, I., Villarroya, F., and Rebollo, L.: Selected papers on aquifer overexploitation, IAH, 392, 1991.
Solís, L., Rodríguez-Estrella, T., Cabezas, F., and Senent, M.: Cálculo de la "curva de explotación" en el sistema acuífero kárstico de la Sierra de Crevillente (Alicante), III Simp. de Hidrog, Vol. IX, Madrid, 345–358, 1983.
UNESCO COMEST: Ethics of Fresh Water Uses, 13 monographs in the Series of Water Ethics, presented in the Third World Water Forum, UNESCO, Kyoto, 2003.
Van Camp, M., Radfar, M., and Walraevens K.: Assessment of groundwater storage depletion by overexploitation using simple indicators in an irrigated closed aquifer basin in Iran., Agr. Water Manage., 97, 1876–1886, 2010.
Wu, J., Shi, X., Ye, S., Xue, Y., Zhang, Y., and Yu, J.: Numerical simulation of land subsidence induced by groundwater overexploitation in Su-Xi-Chang area, China, Environ. Geol., 57, 1409–1421. 2009.

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The problems of overexploitation of aquifers in semi-arid areas

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Table 1. Thermal and chemical characteristics of certain boreholes situated in the subaquifers of Ascoy and Sierra Larga, in recent times.

Boring well	Date	Perm. rock (m)	Conduct. (µS cm^{-1})	Cl^- (mg l^{-1})	Na^+ (mg l^{-1})	Temp. (°C)	Type of aquifer	
							Free	Conf.
CA0709002	6 Oct 2008	0–250	2250	444	275	–	x	
Fonseca I	7 Jan 2008	306–329	1415	335	211	–		x
Fonseca II	5 Jun 2008	306–438	2610	680	304	22.9		x
S.L. 3	8 Dec 2006	500–520	3000	–	–	–		x
S.L. 1	6 Aug 2008	265–344	3920	–	–	28.6		x
Jesús II	1 Mar 2008	0–304	2140	600	600	26.6	x	
Judío I	9 Apr 2009	495–508	2470	–	–	28		x
Judío II	3 Dec 2009	495–691	8110	2344	1456	35.5		x

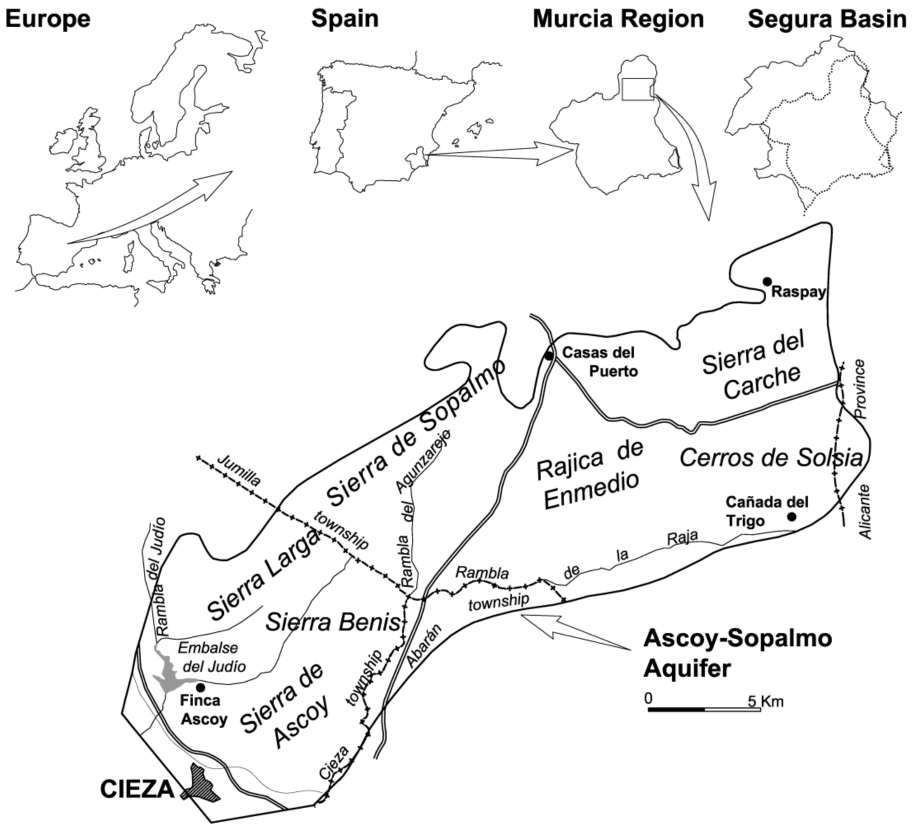

Fig. 1. Location of the Region of Murcia and the Ascoy-Sopalmo aquifer, within Spain and Europe.

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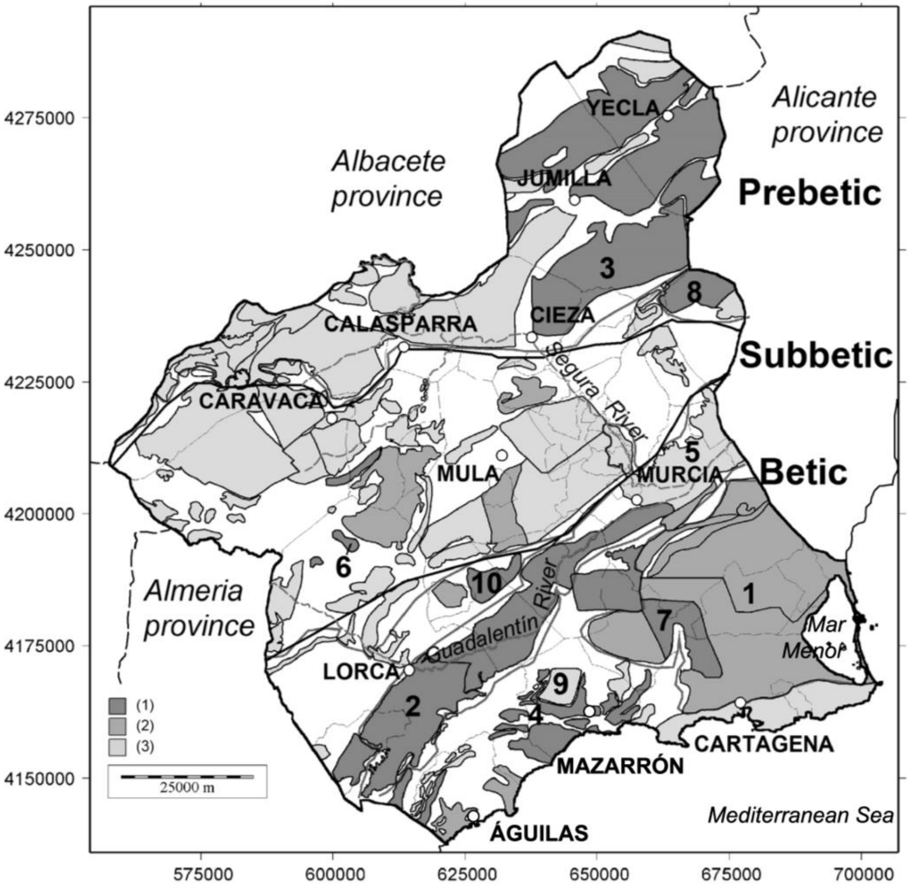

Fig. 2. Map showing aquifer overexploitation in the Region of Murcia. 1: highly overexploited, 2: weakly overexploited, 3: no overexploited (Rodríguez-Estrella, 2004).

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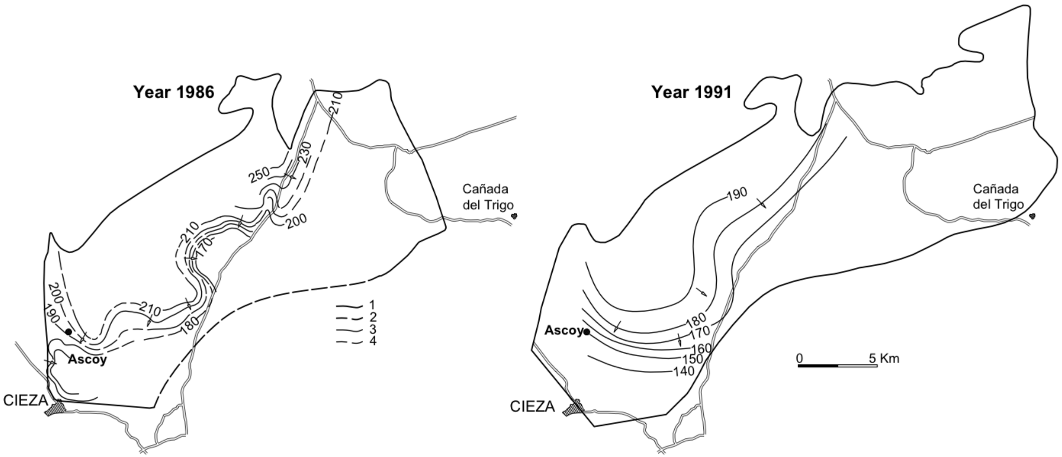

Fig. 3. Water-level contour maps for the Ascoy-Sopalmo aquifer, 1986 (CARM unpublished) and 1991 (IGME, unpublished). 1: limit of aquifer, 2: Supposed limit of aquifer, 3: Water-level contour (m a.s.l.), 4: Supposed water-level contour.

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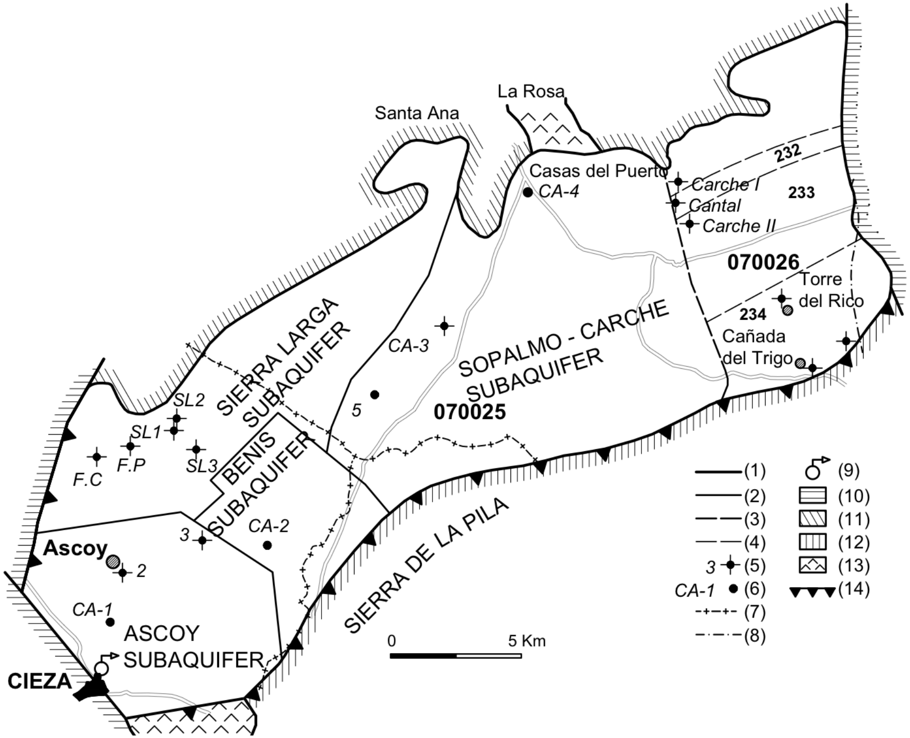

Fig. 4. Hydrogeological compartments or subaquifers in the Ascoy-Sopalmo aquifer since 2004. (1): Border of the Ascoy-Sopalmo aquifer. (2): Border of the hydrogeological compartment or subaquifer. (3): Eastern border of the Ascoy-Sopalmo aquifer until 1989 and of the new unit defined by the CHS. (4) Border of the aquifer within the new hydrogeological unit of the CHS. (5): Piezometric monitoring point. (6): Chemical water quality monitoring point. (7). Limit of the municipality. (8): Provincial border. (9): Old Spring. (10): Upper Miocene marls. (11): Lower Cretaceous clays (impermeable base). (12): Upper Cretaceous and Eocene marls. (13): Triassic clays with gypsums. (14): Thrust fault.

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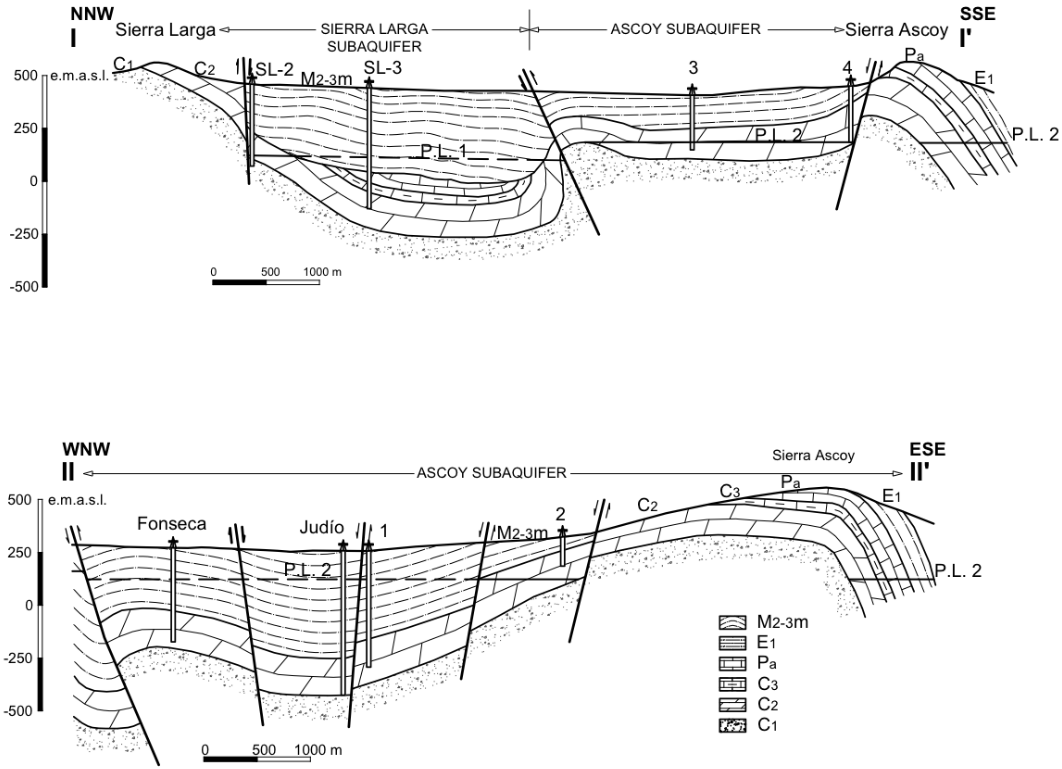

Fig. 5. Hydrogeological section in the subaquifers of Ascoy and Sierra Larga. C1: Clays and sands. LowerCretaceous. C2: Dolomites. Lower-Middle Cenomanian. C3: Marly limestones and limestones. Upper Senonian. Pa: Limestones. Palaeocene. E1: Clays. Lower Eocene. M2-3m: Marls with gypsums. Middle – Upper Miocene. P. L.: Piezometric Level.

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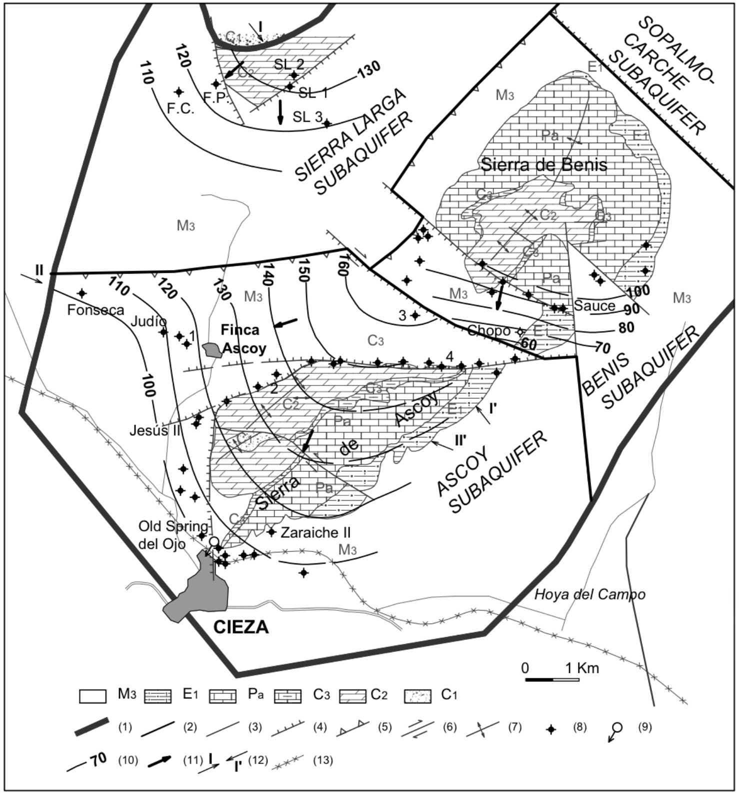

Fig. 6. Water-level contour map (24 November 2004) in the hydrological compartments of Ascoy, Benís and Sierra Larga. M3: Marls. Upper Miocene. E1: Clays and sands. Lower Eocene. Pa: Limestones. Palaeocene. C3: Marly limestones. Upper Senonian. C2: Dolomites. Lower-Middle Cenomanian. C1: Sands and marls. Lower Cretaceous. (1): Limit of the aquifer. (2): Limit of subaquifer. (3): Fault. (4): Normal fault. (5): Reverse fault. (6): Tear fault. (7) Anticlinal. (8): Borehole. (9): Spring. (10) Water-level contour. (11): Groundwater flow. (12): Hydrogeological section. (13) Railway.

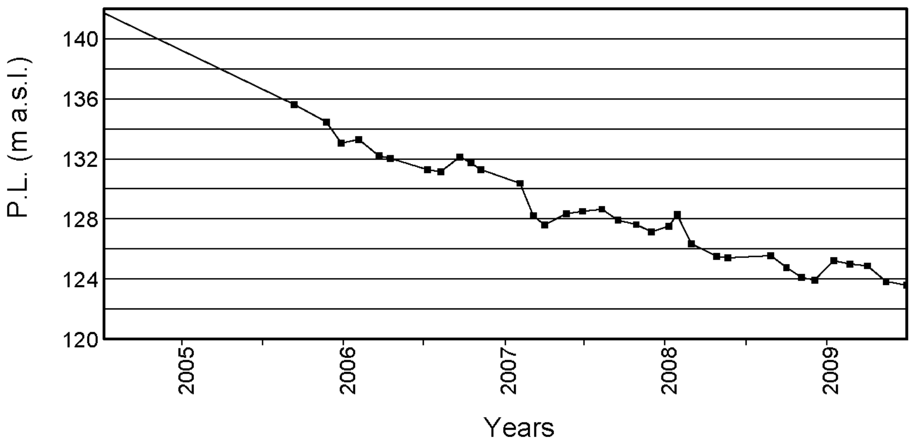

Fig. 7. Groundwater level evolution in the CHS piezometer 2.

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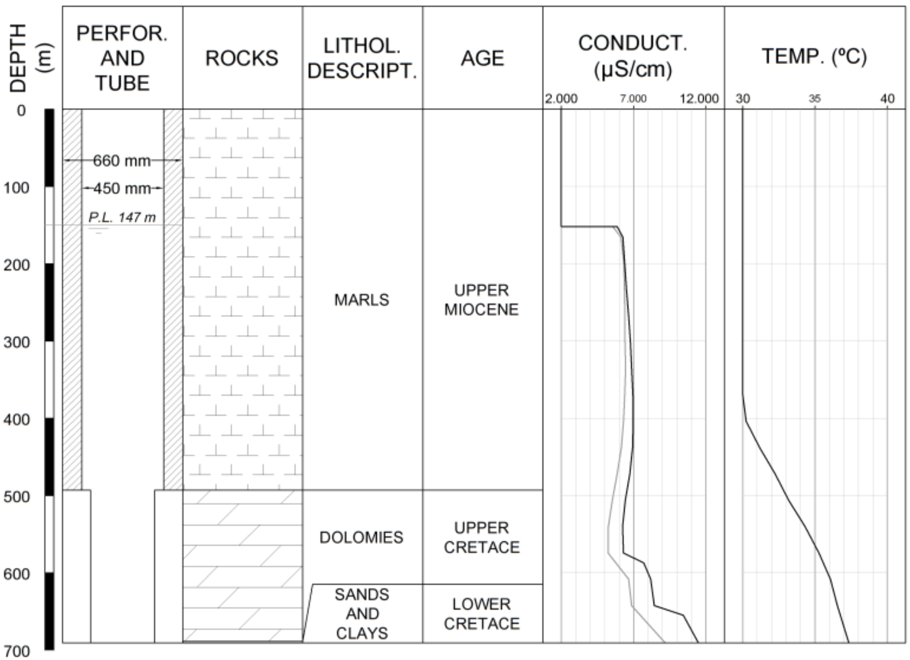

Fig. 8. Log of temperature and conductivity in Judío II boring.

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