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The problems of overexploitation of aquifers in semi-arid areas: characteristics and proposals for mitigation

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ABSTRACT

This article presents a general analysis of the problems arising from overexploited aquifers in semi-arid areas, based on research carried out in the Region of Murcia (one of the most over-exploited areas in Europe). Among the negative impacts of this overexploitation are: the drying up of springs, the continuous drawdown of water levels (up to 10 m/y), piezometric drops (over 30 m in one year if it is a karstic aquifer), an increase in pumping costs (elevating water from a depth of more than 450 m), abandonment of wells, diminishing groundwater reserves, deteriorating water quality, presence of CO_2, compartmentalizing of aquifers, etc. A series of internal measures is proposed to alleviate the overexploitation of the region.

Key words: overexploitation problems, proposals for mitigation, semi-arid areas, Region of Murcia, Spain.

Los problemas de la sobreexplotación de acuíferos en áreas semi-áridas: características y propuestas de mitigación

RESUMEN

Este artículo presenta un análisis general de los problemas que presentan los acuíferos sobreexplotados en áreas semiáridas, basado en la investigación llevada a cabo en la Región de Murcia (una de las áreas más sobreexplotadas de Europa). Entre los impactos negativos de la sobreexplotación, cabe destacar los siguientes: secado de manantiales, descenso continuado de los niveles piezométricos (hasta 10 m/a), caídas piezométricas (alrededor de 30 m en un año si se trata de acuíferos kársticos), incremento en el coste de bombeo (elevaciones de agua desde profundidades superiores a 450 m), abandono de pozos, disminución de las reservas, deterioro de la calidad química de las aguas, presencia de CO_2, compartimentación de acuíferos, etc. Así mismo, se propone una serie de medidas internas con el fin de aliviar la sobreexplotación de la citada Región de Murcia.

Palabras clave: problemas de sobrexplotación, propuestas de mitigación, áreas semi-áridas, Región de Murcia, España.

VERSION ABREVIADA CASTELLANO

Introducción

Dentro del Sureste de España y de la Cuenca del Segura, la Región de Murcia (RM), es una de las más áridas de Europa, ya que presenta en el NW montañoso una lluvia de 650 mm y una temperatura de 13 ºC, pero en el SE costero estos parámetros son de 300 mm y 18 ºC, respectivamente Es también la que mayor sobreexplotación de acuíferos tiene de España.

La RM, de 11 317 km^2, tiene unas entradas hídricas en sus acuíferos de 358 hm^3/año (307 hm^3/año de lluvia y 51 hm^3/año de retornos de regadíos) y unas salidas de 520 hm^3/año (casi 1,5 veces más que los recursos). Del total de estas últimas, 140 hm^3/año corresponden a manantiales y los restantes 380 hm^3/año a agua bombeada. Por lo tanto, hay un déficit hídrico de 162 hm^3/año; sin embargo, la sobreexplotación es de 214 hm^3/año.

De los 125 acuíferos definidos, 30 están sobreexplotados y otros 13 lo estuvieron en su día, por lo que pueden estarlo de nuevo; a este último grupo pertenece el Campo de Cartagena (1/6 de la superficie de la RM). Los 43 acuíferos problemáticos representan casi un tercio del total. Este balance hídrico de la RM (Rodríguez-Estrella, 2004) corresponde al año 1995, que se trata de un año seco (no existe un balance más reciente). La mayoría de los acuíferos sobreexplotados se sitúa en la mitad oriental de la Región de Murcia; existiendo en la misma un eje de simetría que separa dos zonas con características físicas contrapuestas (tabla1)

La figura 1 muestra la situación de la RM, en España y en Europa. En la figura 2 se representa el grado de sobreexplotación de los acuíferos de la RM.

El autor ha realizado investigaciones sobre este tema en el Sureste de España y en la Cuenca del Segura durante 45 años y piensa que transmitir sus experiencias y conocimientos, ya muy próximo al final de su vida profesional, puede ser de utilidad para investigadores de otras áreas que se enfrenten a problemas similares.

El desequilibrio de las aguas subterráneas es mayor en el este y sur de la RM (Valle del Guadalentín, Zona Prebética y Zona Bética), donde las condiciones climáticas son más favorables para el desarrollo de la agricultura moderna y donde los suelos son más fértiles.

Efectos de la sobreexplotación de acuíferos

Este tema fue tratado con detalle por Rodríguez-Estrella (2004). En este capítulo se mencionan acuíferos sobre-explotados de todo el Sureste de España, pero preferentemente de la Región de Murcia.

Efectos positivos de la explotación intensiva

- *Desarrollo económico progresivo.*
- *Beneficios para las infraestructuras.*
- *Reinfiltración de excedentes de regadío.*
- *Recuperación de suelos salinos.*
- *Aumento de la cobertura vegetal.*

Efectos negativos de la sobreexplotación

Directos

- *Descenso continuado de los niveles piezométricos. De hasta 10 m/año, como en el acuífero de Don Gonzalo-La Umbría (figura 3).*
- *Aumento del coste económico del bombeo. En el acuífero del Cabezón del Oro (provincia de Alicante), el agua está a una profundidad próxima a los 300 m (figura 4).*
- *Abandono de pozos.*
- *Disminución de las reservas subterráneas.*
- *Compactación inducida en la superficie.*
- *Compartimentación de acuíferos. Ejemplo, Quibas (figura 5) o Ascoy-Sopalmo (figuras 6 y 7).*
- *Cambio en las características físicas y químicas del agua subterránea. Por ejemplo, de facies sulfatada a bicarbonatada, por la influencia de CO_2 endógeno, en el Alto Guadalentín (figura 8); o aumento de la temperatura en el mismo acuífero (figura 9)*
- *Modificación inducida en el régimen de flujo del río.*
- *Impacto o desecación de humedales y manantiales.*
- *Cambios en los sistemas de extracción de agua subterránea. Ejemplo: Galería de los Suizos en el acuífero de Crevillente (figura 10).*
- *Alteración de las propiedades hidrodinámicas del acuífero.*
- *Creación de conoides*

Indirectos

- *Hundimiento y colapso del terreno*
- *Rotura de tuberías y deterioro de las carreteras.*
- *Salinización de suelos, por ejemplo, en el valle del Guadalentín.*
- *Desertificación progresiva.*
- *Modificación o supresión de la flora.*

- *Desaparición de fauna específica y sustitución por otra.*
- *Abandono de la agricultura y emigración desde pueblos y ciudades.*
- *Disminución o desaparición de los rebaños de ovejas.*
- *Disminución de la caza y la pesca.*
- *Interrupción de la explotación de recursos de los humedales.*
- *Cambios en el paisaje y falta de correlación con antiguos topónimos.*
- *Problemas legales.*
- *Impactos sociales, económicos y políticos de carácter negativo.*
- *Desaparición o deterioro de elementos del paisaje o de características hidrológicas e hidrogeológicas que forman parte del patrimonio nacional (Rodríguez-Estrella 1999).*

Trabajos de exploración para "alargar la vida" de acuíferos fuertemente sobreexplotados, a la espera de encontrar una solución definitiva en el futuro. Ejemplo: el acuífero Ascoy-Sopalmo (el más sobreexplotado de España)

El acuífero de Ascoy-Sopalmo es el más sobreexplotado de España, ya que, frente a unos recursos renovables de 2 hm^3/año, se extrajeron 55 hm^3/año en 1985. Esto ha dado lugar a que: se sequen manantiales; los descensos de niveles piezométricos superen los 5 m/año; las caídas piezométricas sean de más de 30 m/año; se produzca un aumento de los costes de bombeo (ya se eleva el agua desde más de 320 m); se abandonen los pozos (de 45, en 1970, a 20, en 2010); se disminuyan las reservas hídricas subterráneas; y se deteriore la calidad química del agua (ha pasado de tener facies mixta clorurada/bicarbonatada sódica a ser clorurada sódica).

Con el objetivo de resolver provisionalmente los graves problemas que presenta este acuífero, y hasta que se legislen decisiones estatales, se han realizado para mitigar el problema y resolver así en parte los compromisos adquiridos, los siguientes trabajos:

1. *A partir de la observación de las columnas litológicas de los viejos sondeos y de los registros geofísicos efectuados (rayos gamma, calibre, desviación y cámara de televisión), ciertos pozos fueron reprofundizados hasta el impermeable de base, consiguiéndose aumentos sustanciales de caudal.*
2. *Para conseguir obtener perforaciones con visión de futuro se abandonaron los pozos antiguos, que casi todos estaban emboquillados en las rocas permeables de las laderas montañosas (régimen libre), con lo cual gran parte de dichas rocas ya estaban desaturadas. En sustitución se ubicaron pozos nuevos completos en las depresiones, que resultaron ser confinados y presentaron una gran columna de agua.*
3. *Para la mejor ubicación de estos pozos se realizó una campaña de Geofísica previa, en su especialidad de SEV, obteniéndose magníficos resultados, ya que existía un gran contraste resistivo entre las margas miocénicas del techo y las rocas carbonatadas del Cretácico Superior.*
3. *Puesto que los espesores del relleno del impermeable de techo fueron a veces superiores a los 500 m se procedió, como medida de seguridad, a realizar sondeos de investigación, mediante rotopercusión.*
4. *Una vez confirmado que era correcta la interpretación geofísica, se perforaron los pozos profundos (algunos de 700 m) y anchos (tuberías de 550 mm de diámetro) con máquinas de rotación inversa.*
5. *Dado que el sistema de perforación había utilizado lodos, las fisuras en parte obstruidas tuvieron que limpiarse con polifosfatos y posteriormente ser tratadas con ácido clorhídrico.*
6. *Finalmente, se procedió a un bombeo de ensayo, de más de 24 horas, con caudales superiores a los 100 L/s y descensos de menos de 20 metros.*

Propuesta de acciones internas a medio plazo para aliviar problemas de sobreexplotación de acuíferos en zonas semiáridas. Ejemplo: Región de Murcia

Según Rodríguez-Estrella (2004) y Molina et al. (2009), estas acciones podrían ser:

- *Uso combinado de aguas subterráneas con aguas superficiales (figura 11).*
- *Trasvase de agua entre subcuencas o entre acuíferos.*
- *Regulación de manantiales, mediante sondeos.*
- *Extracción temporal de parte de las reservas en acuíferos profundos sin explotar*
- *Redistribución espacial de las extracciones.*
- *Recarga artificial del agua de crecidas.*
- *Constitución de Comunidades de Usuarios de acuíferos y Planes de Ordenación.*
- *Adaptación de la calidad química del agua para su uso final.*
- *Instalación de sistemas de riego más eficientes.*
- *Transformación agraria.*
- *Uso de aguas residuales para el riego, una vez depuradas.*
- *Desalinización de agua de mar en acuíferos costeros.*
- *Informatización de superficies de riego, conducciones y uso del agua.*

Conclusiones

1) El problema de la sobreexplotación en la Cuenca del Segura y, concretamente en la Región de Murcia, no tiene solución a corto plazo, ya que han transcurrido muchos años de afectación y los acuíferos están muy esquilmados: la única posible es la transferencia de recursos hídricos procedentes de cuencas excedentarias; pero esta actuación es inviable en este momento, por problemas políticos.

2) Mientras no se lleve a cabo la propuesta anterior de intercuencas, en este artículo se propone una serie de actuaciones intracuenca, de carácter transitorio, que mitigarán sin duda esta problemática enquistada. En efecto, la aplicación ya de muchas de ellas ha hecho que en los últimos 5 años disminuya la explotación y, en consecuencia, hayan ascendidos los niveles piezométricos hasta incluso 67 m en el acuífero Bosque y 50 m en Santa Yéchar (figuras 12 y 13 y tabla 2).

Introduction

Since 1989, when the conference *Overexploitation of Aquifers* was held in Almeria, Spain (Pulido *et al.*, 1989), and since 1991 when the 13th International Conference of the International Association of Hydrogeologists (IAH) was dedicated to *Aquifer Overexploitation* (Candela *et al.* 1991*,* Simmers *et al.*, 1992) (in both conferences the author presented several articles), a vast number of researchers have shown interest in the problems of overexploitation (Bajjali *et al.*, 2006, Closson *et al.*, 2009, Custodio 1989, 2002, Hani *et al.*, 2006, Hsu *et al.*, 2007, Ibáñez *et al.*, 2008, Molina *et al.*, 2009, 2010, Petit 2004, Praveena *et al.*, 2010, Pulido *et al.*, 1989, 2002, Rodríguez-Estrella 2004, Serrat *et al.*, 2007, Van Camp *et al.* 2010, Villarroya and Aldwell 1998, Gleeson *et al.*, 2010, Malik *et al.*, 2004, Martín-Rosales *et al.*, 2007, Pulido *et al.*, 1999), water sustainability (Zalewski 2002, Das *et al.*, 1997, Koutsoyiannis 2011, Melloul *et al.*, 2000, Yang *et al.*, 2001), water crisis (Sivakumar 2011) and dry-land hydrology (Cudennec *et al.,* 2007).

The Region of Murcia is one of the most arid regions in Europe, with the north-western mountain area having an average precipitation of 650 mm and average temperatures of 13 ºC, whilst in the north-eastern coastal zone these parameters are 300 mm and 18 ºC. It is also one of the worst affected areas in terms of the degree of groundwater overexploitation. The region, covering 11 317 km^2, has an inflow of water resources of 358 Mm^3/y (307 Mm^3/y from rainfall and 51 Mm^3/y from irrigation returns) and an outflow total of 520 Mm^3/y, or one and a half times the inflow (of which 140 Mm^3/y corresponds to natural spring flow and the remaining 380 Mm^3/y corresponds to pumped flow). Thus, there is a water deficit of 162 Mm^3/y. Nevertheless, the total over abstraction of all the aquifers is 214 Mm^3/y. Of the 125 aquifers defined, 30 are overexploited and a further 13 have been exploited and could become so again, even though they are in equilibrium at the moment (the latter group includes the aquifers of Campo de Cartagena (1 in Figure 2), which cover one sixth of the surface area of the region and comprise 43 aquifers – over one third

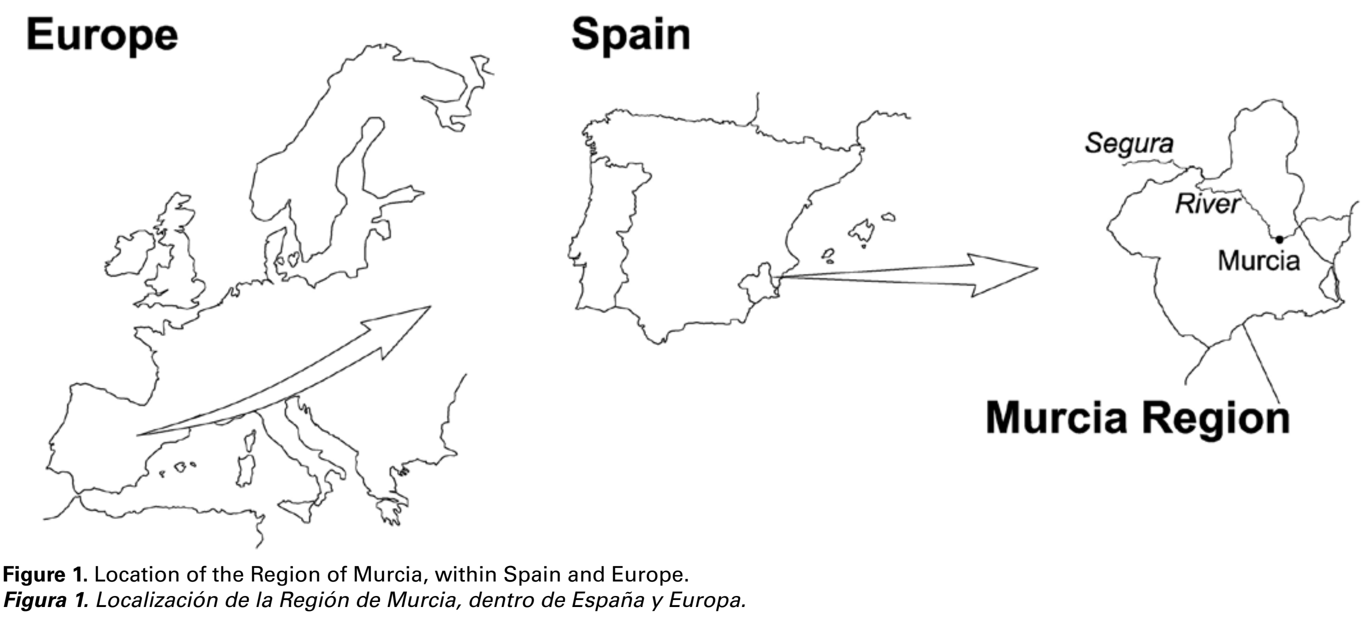

Figure 1. Location of the Region of Murcia, within Spain and Europe.
Figura 1. *Localización de la Región de Murcia, dentro de España y Europa.*

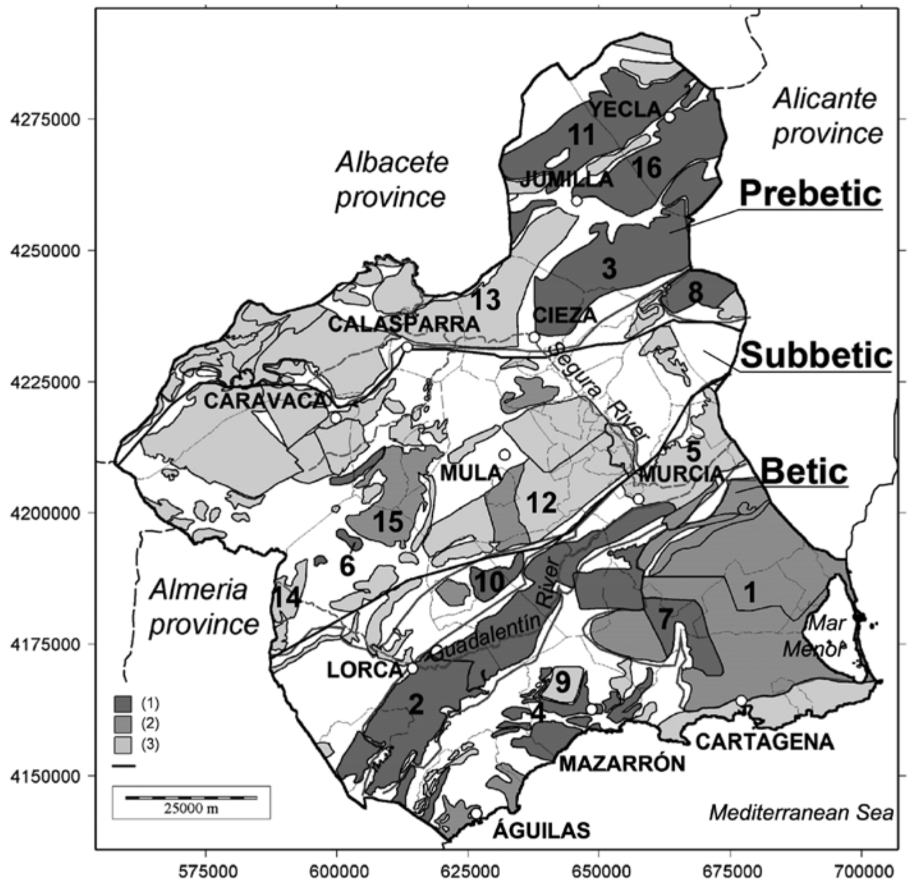

Figure 2. Map showing aquifer overexploitation in the Region of Murcia. 1: Highly overexploited. 2: Slightly overexploited. 3: Not overexploited. 4: Limit of the hydrogeologic unit (Rodríguez-Estrella, 2004).
Figura 2. *Mapa de acuíferos de la Región de Murcia, mostrando el grado de sobreexplotación. 1: Muy sobreexplotado. 2: Débilmente sobreexplotado. 3: No sobreexplotado. 4. Límite de unidad hidrogeológica (Rodríguez Estrella, 2004).*

of the total number). This hydric balance of the Region of Murcia (Rodríguez-Estrella, 2004) corresponds to the year 1995, which was a dry year (no more recent water balance data exists).

Figure 1 illustrates the situation of the Region of Murcia in Spain and in Europe. Figure 2 is a map showing the overexploitation of aquifers in the Region of Murcia.

The author has conducted research on this subject for more than 45 years and suggests that sharing this experience and knowledge will be of use to researchers and representatives from other areas that face similar problems; it may also help prevent such problems occurring in the future.

Geographically, the groundwater imbalance in Murcia is most intense in the east of the region, where climate conditions are most favourable for developing modern agriculture, for which the greatest groundwater abstractions are made. The most significant overexploitations are recorded in the Guadalentín Valley, the Prebetic and the Betic. In the Guadalentín Valley (2 in Figure 2), overexploitation amounts to 66 Mm^3/y (87 pumped abstractions, minus the 21 inflows). In the Prebetic, overexploitation totals 93 Mm^3/y. The situation in the Betic is particularly delicate; here, overexploitation amounts to 25.5 Mm^3/y. The municipality of Mazarrón (4 in Figure 2) poses a special problem due to the extreme depletion of the reserves (these are aquifers of less than 10 km^2 in area) and the deterioration in chemical water quality that is occurring due to marine intrusion.

The Region of Murcia (from west to east, bipolar and symmetrical with a vertical axis) has varied and contrasting physical properties, as follows (Table 1):

Based on the definition given by Pulido (2001), I can extrapolate that the 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 a negative impact on the physical and biotic environments; all this refers to a sufficiently long period (25 years for southeast 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 levels (Rodríguez-Estrella, 2004).

Feature	West	East
Relief	Rugged	Soft
Rain/rainfall	Heavy	Scarce
Temperatures	Low	High
Rivers	Large	Small
Soil	Little and poor	Abundant and fertile
Demand	Scant	Great
Resources	Abundant	Sparse
Reserves	Scarce in general	Abundant in general
Chemical quality	Good	Poor to bad
Overexploitation	No	Yes

Table 1. The physical properties of the Murcia Region.
Tabla 1. *Propiedades físicas de la Región de Murcia.*

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). I am against using this term, since the word "intensive", according to the dictionary, means "more intensive, energetic or active" but does not imply "exceed, go above", whilst "overexploitation" does. The prefix "over" means "above, beyond" and the word "exploit" is equivalent to using "to one's own advantage", generally in an abusive way (abuse = ill usage, excessive or improper use). Thus, the word "overexploitation" implies excessive or improper use (transgressive), which is what it means. In contrast, "intensive use" can mean energetic but not transgressing the state of equilibrium.

Effects of aquifer overexploitation

I propose that the term intensive exploitation be used to refer to the phase preceding overexploitation: thus as a consequence of one, the other arises. Although, the first does not necessarily have to culminate in the second; there could be an intensive exploitation alternating with periods of zero abstraction that would never lead to overexploitation.

In many cases, intensive aquifer exploitation includes an initial phase that has positive effects but, over a period of 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.

In this paper I consider cases mainly from the Region of Murcia, though I also refer to other provinces in the south-east of Spain, including Alicante and Albacete.

Positive effects of intensive exploitation

- *Progressive economic development*. The district of Mazarrón (4 in Figure 2) suffered economic depression between 1900 and 1950. In 1989, thanks to intensive exploitation of its aquifers (the Tagus-Segura water transfer scheme had not yet arrived), it achieved an agricultural production worth €102 M, with profits/income of €67 M (Aragón *et al.*, 1992).
  The real problem of overexploitation arises from the uncertainty of maintaining the socio-economic develo*pment in the long term, especially if there is no prospect of external water resources being supplied to a particular area.*
- *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. In Vega del Segura (5 in Figure 2), the irrigation excess amounts to 25-35% of the water applied, if the irrigation system is gravity fed.
- *Recovery of saline soils* (as there is more water, there is greater solution). For example, in the Guadalentín Valley, with the introduction of groundwater irrigation, areas of previously sterile soil, namely the salt flats of Altobordo and Los Ventorrillos, were invaded and converted into fertile areas.
- *Increase in vegetation cover,* which improves rainfall infiltration. In the same case as above, the sparse whitish areas of the salting have been populated by a thick tree cover.

Negative effects of overexploitation

Direct

- *Continuous fall in piezometric levels*. Of up to 10 m/y (Figure 3), as in the aquifer of Don Gonzalo, La Umbría (6 in Figure 2).
- *Increase in the economic cost of pumping*. In the Triassic aquifer, Las Victorias (7 in Figure 2), or in the aquifer of the Cabezón del Oro (province of Alicante), where the piezometric level now lies below 300 m deep. (Andreu *et al.,* 2004). The boreholes are more than 500 m deep and two pumps, operating in series, are required to extract the water. Figure 4 shows the situation in

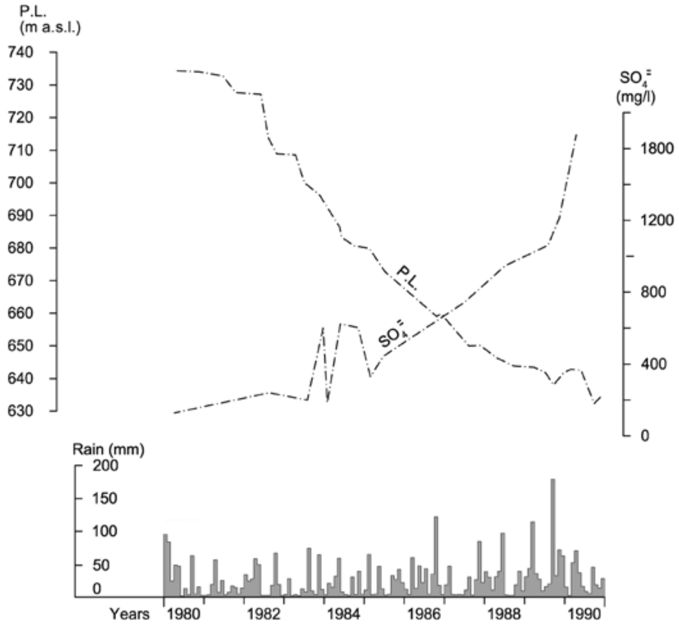

Figure 3. Evolution of the piezometrical level and sulphates in the Don Gonzalo-La Umbría overexploited aquifer.
Figura 3. *Evolución del nivel piezométrico y sulfatos en el acuífero sobreexplotado de Don Gonzalo-La Umbría.*

1963 when pumped abstractions had not yet begun; under this natural regime, the aquifer was discharging water from the thermal spring at Aguas de Busot, and feeding the thermal spa of the same name. Logically, the fall in the piezometric level has been deduced by taking the elevation of the spring as the point of reference.

– *Abandonment of wells*. In 1971 in the Ascoy-Sopalmo aquifer (the focus of this paper), there were 146 production wells; by 1987, only 60 were still active, and now (2010), there are fewer than 20. The reason that these wells were abandoned was the fall in the piezometric level, which left them dry, and the high cost that would have been incurred to drill such deep substitution wells.
– *Diminishing groundwater reserves*. Between 1975 and 1981, 210 Mm^3 were taken from the reserves held in the Alto Guadalentín aquifer (Puerto Lumbreras and Lorca).
– *Induced compaction of the land surface* and appearance or accentuation of endorrheic or semi-endorrheic areas. Within the Alto Guadalentín aquifer, there is a significant semi-endorrheic basin in Altobordo, which has become more accentuated in recent times as a consequence of the high concentration of boreholes located in this vicinity. This explains the abundance of aligned "piping" (Photo 1) and collapses that would have accompanied the subsidence; this phenomenon is basically due to the oversaturation provoked by the overexploitation of the aquifer. Something similar has occurred in the Saltings of Mata de los Ventorrillos, in the same valley (Rodríguez Estrella *et al.*, 1996), where the subsidence caused by overexploitation of groundwater has been recently confirmed using European Space Agency satellite technology and was estimated to be between 1.5 cm/year, between 1992 and 2006.

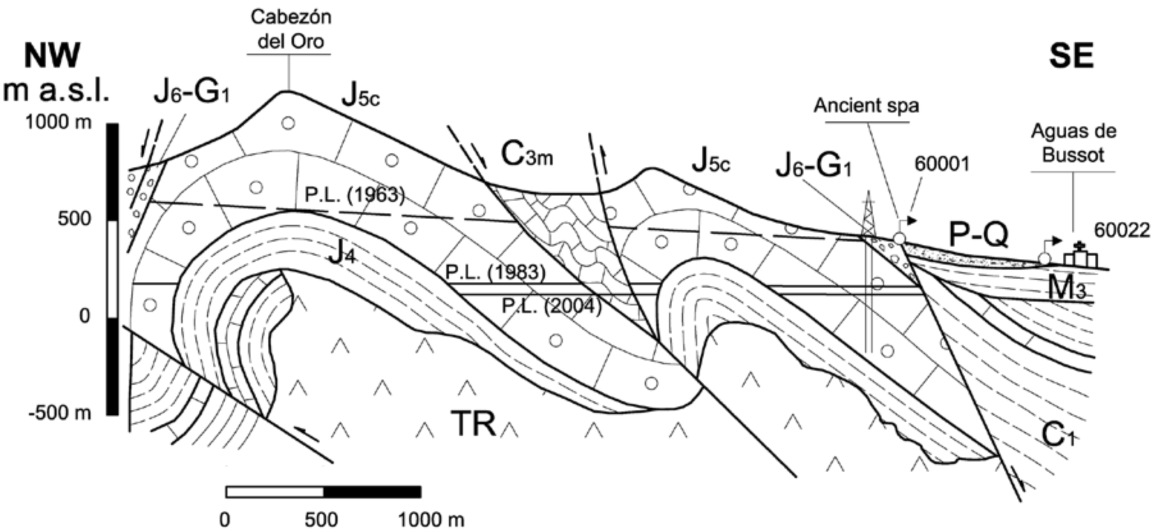

Figure 4. A hydrogeological section of the Cabezón del Oro overexploited aquifer. TR: Clay and gypsum. Triassic. J_4: Marly limestone. Middle Jurassic. J_{5c}: Oölitic limestone. Upper Jurassic. J_6-G_1: Sandstone. Upper Jurassic-Lower Cretaceous. C_1: Marls. Lower Cretaceous. C_{3m}: Marly limestone. Upper Cretaceous. M_3: Marls. Upper Miocene. P-Q: Conglomerates. Pliocene-Quaternary.
Figura 4. *Corte hidrogeológico en el acuífero sobreexplotado de Cabezón de Oro. TR: Arcillas y yesos. Triásico.* J_4*: Margocalizas. Jurásico Medio.* J_{5c}*: Calizas oolíticas. Jurásico Superior.* J_6-G_1*: Areniscas. Jurásico Superior-Cretácico Inferior.* C_1*: Margas. Cretácico Inferior.* C_{3m}*: Margocalizas. Cretácico Superior.* M_3*: Margas. Mioceno Superior. P-Q: Conglomerados. Plio-Cuaternario.*

Photo 1. Erosion gullies and alined soil piping in the Guadalentín Valley.
Foto 1. *Estructuras erosivas en tragadero ("piping") en el Valle del Guadalentín.*

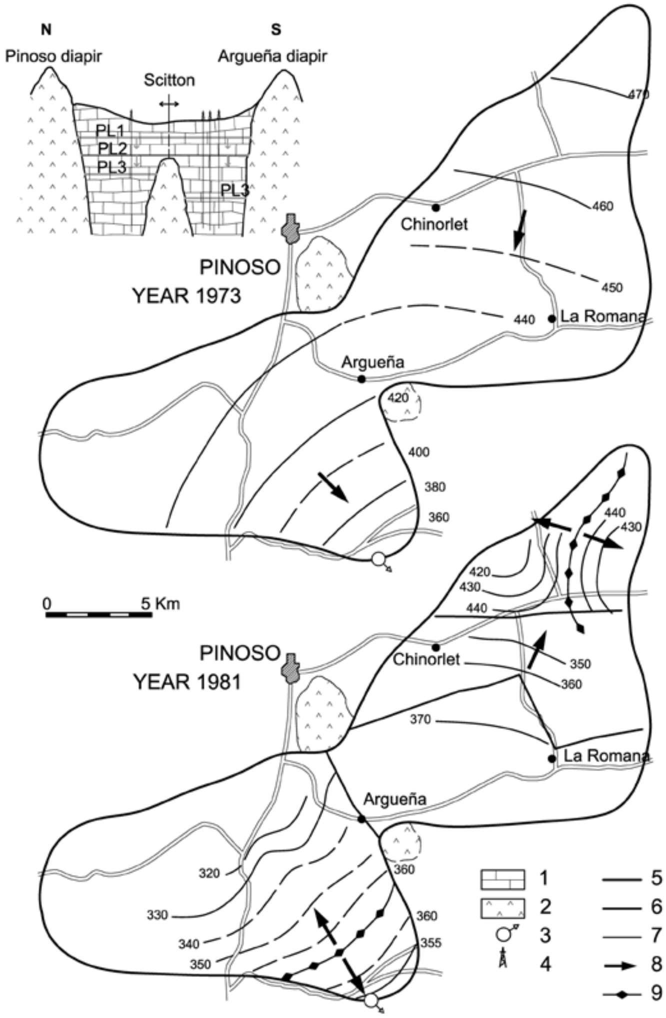

Figure 5. Water-level contour maps and the hydrogeological scheme of the Quibas aquifer. 1: Limestone. Eocene. 2: Clay and gypsum .Triassic. 3: Chícamo spring. 4: Boring. 5: Limit of aquifer. 6: Limit of sub-aquifer. 7: Water-level contour (m a.s.l.). 8: Groundwater flow. 9: Groundwater division.
Figura 5. *Mapa de isopiezas y esquema hidrogeológico del acuífero de Quibas. 1: Calizas. Eoceno. 2: Arcillas y yesos. Triásico. 3: Manantial del Chícamo. 4: Sondeo. 5: Límite de acuífero. 6: Límite de subacuífero. 7: Isopieza (m s.n.m.). 8: Sentido de flujo. 9: Divisoria de aguas subterránea.*

- *Land subsidence and collapse,* giving rise to geotechnical impacts on dwellings (Cooper 1998). During the 1994 drought, numerous emergency wells were brought into operation in the Quaternary Vega Media aquifer in Murcia province. The consequence was a drop in piezometric levels of up to 7 m, and land subsidence and ground collapse of up to 0.7 m, causing cracks to appear in buildings in the city of Murcia.
- *Compartmentalization of aquifers*. In 1973, the Quibas aquifer (8 in Figure 2; Murcia and Alicante provinces), extended over 317 km^2 and was drained by the Chícamo spring (Figure 5).
  In 1980, it split into six distinct sub-aquifers as the falling piezometric level sank below the top of the Triassic diapiric sub-outcrops (Rodríguez-Estrella, 2004). The same thing has happened in the Ascoy-Sopalmo aquifer; at present this aquifer has split into four independent sub-aquifers, defined by large-throw faults (Figures 6 and 7).
- *Change in the physical and chemical characteristics of the groundwater*. Of these, the following are considered:
  - *From bicarbonate to sulphate or chloride facies:* through lixiviation of continental evaporites, e.g., Don Gonzalo-La Umbría aquifer (Figure 3); through marine intrusion, e.g., Cabo Roig (Alicante province).
  - *From a sulphate to a bicarbonate facies:* through the influence of endogenic CO_2, e.g., Alto Guadalentín (Figure 8 and Photo 2). Highly mineralized waters, situated in depths, are propelled upwards by the action of the CO_2 and by the decrease in the hydrostatic pressure, and also as a consequence of the decrease in the piezometric levels (Rodríguez-Estrella *et al.*, 1987, Cerón *et al.,* 1999).
  - *Increase in temperature*, e.g., Alto Guadalentín and Ascoy Sopalmo; in the latter, the confined nature of the aquifer combined with its depth

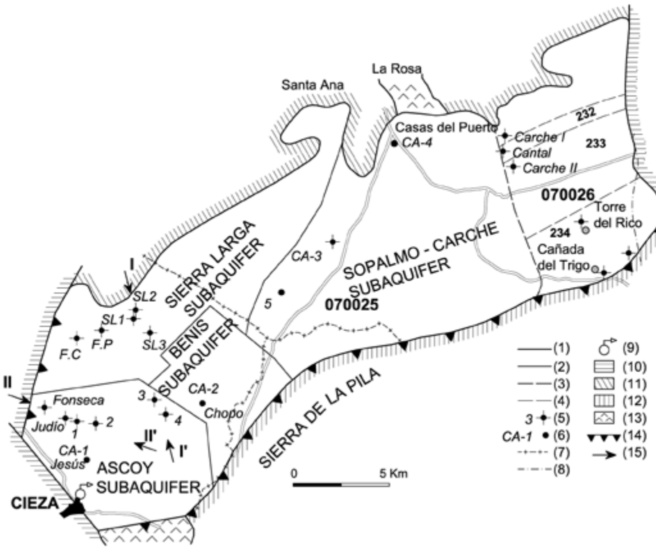

Figure 6. The hydrogeological compartments or sub-aquifers in the Ascoy-Sopalmo overexploitated aquifer since 2004. (1): The border of the Ascoy-Sopalmo aquifer. (2): The border of the hydrogeological compartment or sub-aquifer. (3): Eastern border of the Ascoy-Sopalmo aquifer until 1989 and of the new 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 Cretace clays (impermeable base). (12): Upper Cretace and Eocene marls. (13): Triassic clays with gypsums. (14): Thrust fault. (15): Hydrogeological section.

Figura 6. *Compartimentos hidrogeológicos o subacuíferos en el acuífero sobreexplotado de Ascoy-Sopalmo (Desde 2004). (1): Límite del acuífero de Ascoy-Sopalmo. (2): Límite hidrogeológico de compartimentos o subacuíferos. (3): Límite oriental del acuífero Ascoy-Sopalmo hasta el 1989 y de nuevas unidades definidas por la CHS. (4): Límite de acuífero, dentro de las nuevas unidades hidrogeológicas de la CHS. (5): Punto de control piezómétrico. (6): Punto de control de calidad química. (7): Límite de término municipal. (8): Límite de provincia. (9): Manantial antiguo. (10): Margas del Mioceno Superior. (11): Arcillas del Cretácico Inferior (impermeable de base) (12) Margas del Eoceno y Cretácico Superior. (13): Arcillas y yesos del Triásico. (14): Falla inversa. (15): Corte hidrogeológico.*

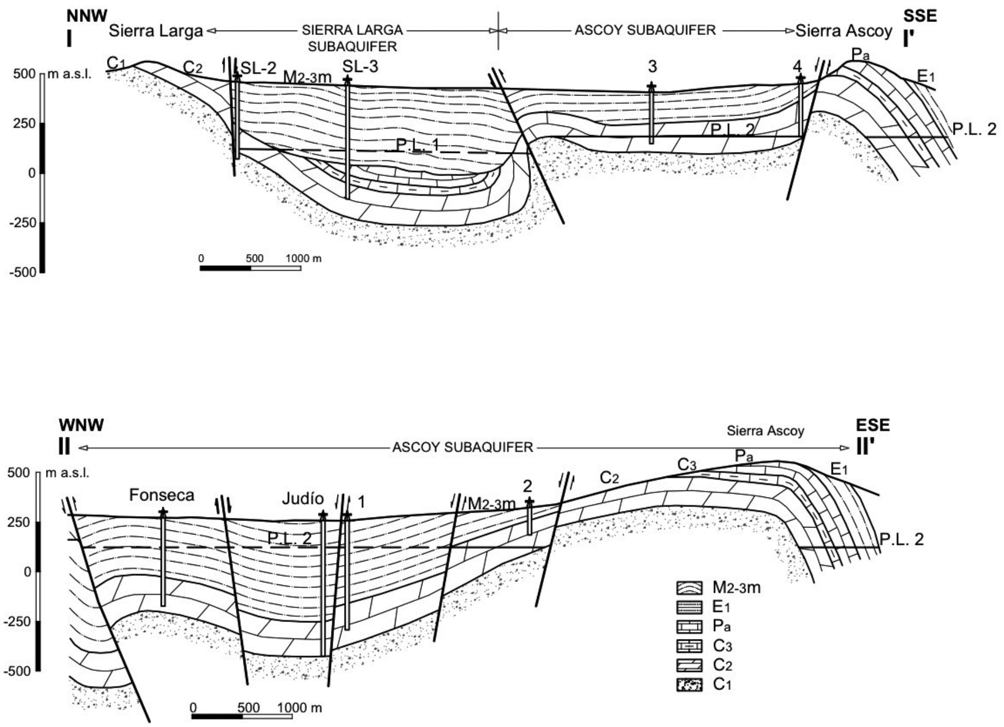

Figure 7. Hydrogeological sections in the Ascoy-Sopalmo overexploited aquifer. C_1: Clays and sands. Lower Cretaceous. C_2: Dolomites. Lower-Middle Cenomanian. C_3: Marly-limestones and limestones. Upper Senonian. Pa: Limestones. Palaeocene. E_1: Clays. Lower Eocene. $M_{2\text{-}3}$m: Marls with gypsums. Middle–Upper Miocene. P.L.: Piezometric Level.

Figura 7. *Cortes hidrogeológicos del acuífero sobreexplotado de Ascoy-Sopalmo. C_1: Arcillas y arenas. Cretácico Inferior. C_2: Dolomías. Cenomaniense Inferior-Medio. C_3: Margocalizas y calizas. Senoniense Superior. Pa: Calizas. Paleoceno. E1: Arcillas. Eoceeno Inferior. $M_{2\text{-}3}$m: Margas con yeso. Mioceno Medio-Superior. P.L: Nivel Piezométrico.*

means that, below a certain depth, the groundwater temperature increases, as does the degree of dissolution and salinity. In the case of the Alto Guadalentín, and specifically in the area around Estación de Puerto Lumbreras, water from borehole 2539-20005 had a temperature of 25 ºC in 1975, which had risen to 35.5 ºC (16 March,1984). Figure 9 is an isotherm map of the Alto Guadalentín aquifer, corresponding to the end of 1986/beginning of 1987.

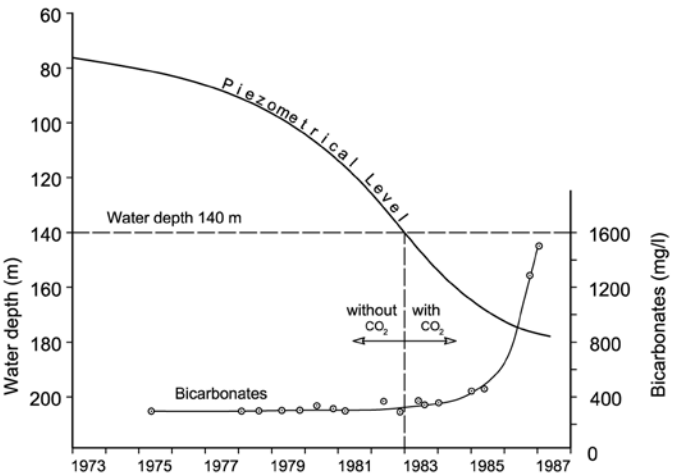

Figure 8. The evolution of the piezometrical level and bicarbonates in the Alto Guadalentín overexploited aquifer.
Figura 8. *Evolución piezométrica y de bicarbonatos en el acuífero suobreexplotado del Alto Guadalentín.*

Photo 2. Endogenous carbonic gas in the Alto Guadalentín aquifer.
Foto 2. *Gas carbónico endógeno en el acuífero del Alto Guadalentín.*

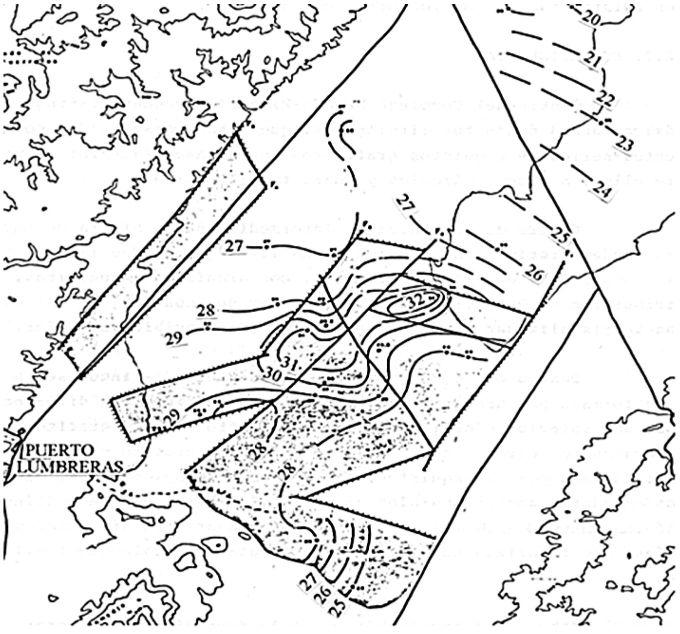

Figure 9. Isoterms in the Alto Guadalentín aquifer (1986-87).
Figura 9. *Isotermas en el acuífero del Alto Guadalentín (1986-87).*

- *Increase in sulphate, dry solids and chlorides; and decrease in calcium and bicarbonates*, e.g., the Saladillo borehole (9 in Figure 2), which is a thermal and emergent borehole (confined aquifer), 535 m deep, which, with the passage of time, has gradually reduced its volume, remaining unaltered by pumping. This is because the emergent volume overcomes the renewable resources, since the main permeable rock does not come to the surface. In addition, between 1985 and 2003, the sulphates increased from 3,093 to 3,579 mg/l; dissolved solids from 9,340 to 9,794 mg/l; chlorides from 1,191 to 1,269 mg/l; calcium, from 713 to 344 mg/l and bicarbonates from 2,068 to 1,989 mg/l. This situation is "natural" overexploitation, not induced by people through pumping, but caused initially by people through the drilling of the borehole and through the slow emptying process of a semi-fossil aquifer (Photo 3).
- *Reduction in temperature*, e.g., Saladillo borehole; between 1985 and 2003 the temperature decreased from 51 ° C to 49 ° C. This was in response to the fall in water pressure that occurred as the groundwater reservoir was partially evacuated. As the geothermal water under pressure rises in smaller quantities it takes longer to reach the surface, and is thus less hot when it finally reaches the surface.
- *Modification induced in the river flow regime*. The Albacete hydrogeological unit is in a hydraulic connection with the Júcar River. As a result of overexploitation, the flow of the Júcar River fell from more than 11 m^3/s in 1975 to 5.2 m^3/s in 1989.
- *Impact or desiccation of wetlands and springs*. Numerous wetlands and an even greater number of springs have dried up as a consequence of overexploitation, both in the Albacete and Murcia provinces (López Bermúdez *et al.*, 1988, Navarro *et al.*, 1988). Cases include, in the 1970s for example, the disappearance of the Acequión and Ojos de San Jorge lagoons in Albacete Province (Navarro *et al.,* 1988) and the Salobral lagoon (López Bermúdez *et al.,* 1988).

Photo 3. A thermal, emergent borehole in the confined Saladillo aquifer.
Foto 3. *Surgencia termal en un sondeo del acuífero confinado del Saladillo.*

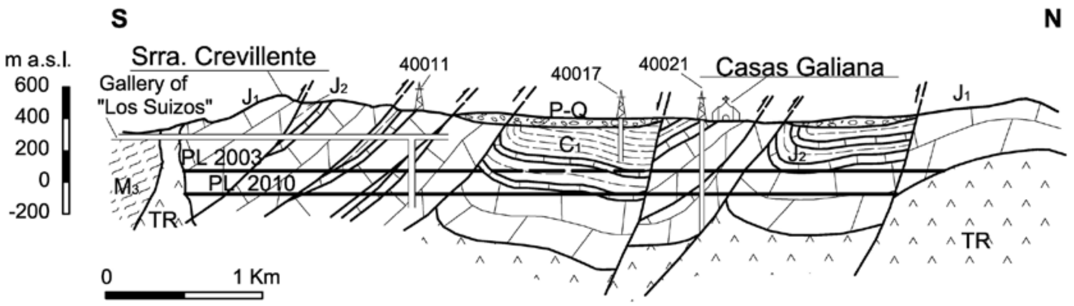

Figure 10. Hydrogeological Section in the Sierra de Crevillente Overexploited Aquifer. TR: Clay and gypsum. Triassic. J_1: Dolomites. Lower Jurassic. J_2: Marls and limestones. Upper Jurassic. C_1: Marls. Lower Cretaceous. M_3: Marls. Upper Miocene. P-Q.: Conglomerates. Pliocene-Quaternary.
Figura 10. *Corte hidrogeológico en el acuífero sobreexplotado de Sierra de Crevillente. TR: Arcillas y yesos. Triásico. J_1: Dolomías. Jurásico Inferior. J_2: Margas y calizas. Jurásico Superior. C_1: Margas. Cretácico Inferior. M3: Margas. Mioceno Superior. P-Q: Conglomerados. Plio-Cuaternario.*

Likewise, sizeable springs (Q>100 l/s) dried up in Murcia Province: in the Ascoy-Sopalmo aquifer (Ojo and Zaraiche el Mayor springs), in the Cingla-Cuchillo aquifer (Jumilla spring; 11 in Figure 2) and in the El Bosque aquifer (Anguilas spring; 12 in Figure 2).

- *Changes in groundwater extraction systems*. Examples include: from ordinary wells (sometimes powered using the natural energy of windmills, as in the Campo de Cartagena) to boreholes; from springs to galleries; from boreholes to galleries, such as the well-known 2500 m Galería de los Suizos in the Crevillente aquifer (Alicante) and also from boreholes within a gallery (Solís *et al.*, 1983). The monumental structure shown in Figure 10 illustrates the extent to which groundwater is a scarce and precious resource in south-eastern Spain.
- *Alteration of the hydrodynamic properties of the aquifer* (water mixing, acceleration of karstification, reduced storage coefficient, etc.). Example: in the Ascoy-Sopalmo aquifer, test pumping in the 1970s gave an effective porosity of 10 % (in the "Jesús" borehole, for example), while by 2007 this parameter had fallen to 7.4 % in the same borehole.
- *Creation of drawdown cones* that mobilize pollutants from remote areas. Example: in the Puerto Lumbreras station of the Alto Guadalentín aquifer, the drawdown cone is some 4 km in diameter and 20 m deep.

Indirect

– *Pipeline breakages and deterioration of road surfaces.* Such damage is common in the Guadalentín Valley.
– *Salinization of soils, e.g., the Guadalentín Valley.*
– *Progressive desertification.* In the Guadalentín Valley, erosion gullies and "soil piping" are common, indicating an advanced stage of desertification (Martínez-Mena et al., 2001). According to Rognon (1996) desertification is defined as "a rapid and sometimes irreversible degeneration of arid and semiarid environments under the effect of an excessive exploitation of its natural resources, which provoke the establishment of ever-more unfavourable conditions for living beings. It is the advance of a desert". There is a very close relationship between aquifer overexploitation and desertification; thus desertification can cause groundwater reserves to dwindle even more, whilst aquifer exploitation can lead to a drop in piezometric levels and so lead to desertification. According to Rodríguez Estrella (2004), desertification can even occur at an early stage of overexploitation, though only in aquifers where the water table lies near the surface (if the natural phreatophytes are not replaced by more or less permanent crops; or simply if the water is used to irrigate in a different aquifer area than the one from which it was extracted). It has already been noted that intensive exploitation can have positive effects; however, if the extracted water is not applied over the same aquifer, the effect on soils and vegetation can be negative. Very frequently, desertification occurs at an advanced phase of overexploitation, when the water taken is increasingly mineralized and causes salinization of the soil (this case depends on the presence or not of intercalated salts at the limits of the aquifers).
– *Modification or suppression of flora*. Change from phreatophytes to xerophytes.
– *Disappearance of a particular fauna and substitution by another.* Substitution of the lacustrine

avifauna by steppe birds in the Guadalentín Valley (Rodríguez-Estrella and López Bermúdez 1992).

– *Abandonment of agriculture and emigration from towns and villages.* Overexploitation of the Jumilla-Villena aquifer in the municipality of Yecla has meant that hamlets, such as Casas de Palao, Hoya del Pozo and Pinillos, which during the 1970s each had nearly 300 inhabitants living from agriculture, now have barely 20 due to emigration.
– *Decline or disappearance of sheep flocks.* The development of sheep husbandry normally goes in parallel with agriculture, so that when agricultural activity ceases, so do numbers of livestock: this has been the case in the Yecla municipality, mentioned above.
– *Decline of hunting and angling.* With the disappearance of surface water, hunting and fishing also disappear.
– *Cessation of wetland-resource exploitation* linked to industries of salt, clay and mineral water spas.
– *Change in landscape and lack of correlation with ancient place names, e.g.,* the villages of Fuente Álamo or Fuente del Pino (Jumilla) no longer have fuentes (springs).
– *Legal problems f*rom impact on water abstraction points.
– *Negative social, economic and political impacts.* The Region of Murcia has seen serious altercations, including a number of deaths related to water resource issues. In the Region of Murcia, disputes are well known between irrigators of one well and users of another well that affects the first (by reducing its flow or drying it up), when abstractions are intensive (Bullas, Mula, Ricote, Zarzadilla de Totana, etc.).
– *Disappearance or deterioration in landscape features or hydrological and hydrogeological features that formed part of the national heritage* (Rodríguez-Estrella 1999), including: old springs with associated archaeological remains that have disappeared; unique ecosystems dependent on springs that have disappeared; ancient lakes with paleontological remains that have dried up; wetlands that have disappeared permanently and which have become dry saline areas; wetlands that have disappeared permanently, being transformed into agricultural areas; wetlands that have disappeared temporarily inside Natural Parks; unusual boreholes of scientific, touristic or educational interest (artesian and thermal wells) that have reduced in flow and temperature.

Exploration works to "extend the useful life" of seriously overexploited aquifers for as long as possible, in the hope that a definitive solution will be found in the future.

Example: the Ascoy-Sopalmo aquifer (the most overexploited in Spain)

In south-east Spain and in particular the Region of Murcia, there are some demands already consolidated (agricultural and public supplies), which cannot be left unresolved. The fact that these demands are met by groundwater has led to overexploitation in many aquifers. In 2003 measures were proposed to avoid this negative effect in the Spanish National Hydrological Plan, such as the transfer of surplus waters from the Ebro River, and the desalination of seawater. As a consequence of the change of the Spanish government in 2004, the first measure was paralyzed, whilst the latter was enhanced, although it became insufficient and expensive.

The Ascoy-Sopalmo aquifer, the most overexploited in Spain, has suffered intense exploitation over the last forty years, it has given renewable water resources of 2 Mm^3/y and abstractions amounting to as much as 55 Mm^3/y. This has resulted in springs drying up, continuous drawdown of water levels (5 m/y), piezometric drops (over 30 m in one year, as a consequence of it being a karstic aquifer), an increase in pumping costs (elevating water from a depth of more than 320 m), abandonment of wells (45 reduced to 20), diminished groundwater reserves and deteriorating water quality (progressing from a mixed sodium bicarbonate-chloride to a sodium chloride facies).

With the aim of provisionally solving the serious problems that this aquifer presents, until this overexploitation problem is definitely overcome by means of state decisions, the following tasks have been carried out:

1. First, from the lithological columns of the old boreholes and in the borehole logs (gamma rays, calliper, deviation and television camera), certain wells were deepened as far as the impermeable base, taking advantage of existing electrical installations and pipework. Thus, the Jesús and Chopo boreholes were deepened (from 145 m to 304 m and 328 m to 460 m, respectively), with substantial increases in flow.
   In 2005, there was a piezometric drop in the Chopo borehole. The base of the well lay in the Lower-Middle Cenomanian dolomite and, given that there only remained 32 m of the water column, it was necessary to deepen the well in January 2006. Below 386 m, it intercepted some Vraconian dolomitized limestone, penetrating

various karstified sections (samples could not be taken), some of which were 20 m thick. This was a very productive borehole (100 l/s with only a 10 m drawdown).

2. However, in order to maintain wells with some sort of future, the wells penetrating the permeable mountain outcrops that were already desaturated (the old wells were located on the mountain slopes) had to be closed down, and new ones placed in the depressions – with the aim of saturating completely these permeable rocks at a certain depth. This was a very risky strategy, since the thickness of the Marly Miocene fill was unknown. Geophysics (SEV) was brought into play, yielding excellent results since there was a strong contrast in resistivity between the Miocene marls (5-15 Ω/m) and the saturated carbonate rocks of the Upper Cretaceous-Palaeocene (80-100 Ω/m).
3. Using the geophysical data, the drilling sites were marked out. However, although the geophysics data was quite conclusive, it was decided to drill investigation boreholes (using rotary drilling) to check the interpretation was correct that had been attributed to the geophysics since, at such great depths, risks were large. In all cases, there was close coincidence. These investigation boreholes only "scratched the surface" of the aquifer. Having confirmed the depth of permeable rock, the boreholes had to be stopped since, in confined aquifers such as this one, the water rises with great pressure, preventing the compressor raising the detritus, and so interrupts the circulation.
4. Having confirmed that the interpretation of the geophysics was correct, the deep wells were fully drilled (using reverse circulation rotary drilling) and some of them reached nearly 700 m.
5. Given that the drilling system had used mud, the semi-obstructed fissures had to be cleaned using polyphosphates.
6. After deepening the Jesús borehole, its flow was gauged. In contrast to what was expected (some fissured zones had appeared), the flow recorded was only 39 l/s with a drawdown of 112 m, whereby the water level fell as far as the screen of the pump. The hole was then treated with hydrochloric acid and, in spite of the aquifer comprising principally dolomites, the results were excellent, achieving a flow of up to 89 l/s with a drawdown of only 50 m. This was due to the existence of numerous fissures, many of them filled with calcite, and the acid enlarged the karstic conduits. With such a positive result, all subsequent well deepening and new boreholes were treated with acid.
7. Finally, the borehole was measured and, since its hydraulic behaviour was demonstrated quickly, a 24 h test pumping was sufficient. Flows were 100 l/s with a drawdown of less than 20 m.

Proposal for internal actions in the medium term to alleviate the problems of overexploitation of aquifers in semi-arid areas, e.g. The Murcia Region

Practically the whole of the Autonomous Region of Murcia is in the Segura Basin. Thus, when considering water-resource management, it is necessary to refer to this basin, whilst examples referred to in this section refer to the Murcia Region.

There is no doubt that the high deficit in the Segura Basin can only be resolved by using water from the Ebro River (i.e., the water flowing into the sea, which is more than 10 000 Mm^3/y). However, until this water is obtained, a series of internal actions can be carried out (Rodríguez-Estrella 2004, Molina *et al.*, 2009), such as:

– *Combined use of groundwater with surface water*
  a) *Groundwater with river water*
     In fact, this has been done since 1991 by the Segura Water Authority (CHS) at the karstic aquifer of the Sinclinal of Calasparra (13 in Figure 2) taking advantage of its hydric relation with the Segura River (Rodríguez-Estrella 1979, Rodríguez-Estrella *et al.*, 2005). Volume units of up to 50 Mm^3/y were extracted in six to eight months (20 boreholes with flows of 100 to 150 l/s, which were marked by the author), and the piezometric level was recovered once the pumping stopped (in winter), since the river feeds the aquifer (Figure 11).
  b) *Groundwater with reservoir superficial waters*
     This was suggested by the author to the Lorca Irri*gation Community, in 1995, considering the hydric* relation existing between the Valdeinfierno reservoir (which at that time was dry) and its underlying aquifer of Pericay-Luchena (14 of Figure 2, with 1000 Mm^3 of reserves (Rodríguez-Estrella 2004).

– *Intra-basin water transfer*. Whenever this idea has been proposed by the author, it has caused discomfort and irritation among inhabitants who are forced to give water to other regions, which have a deficit within the same basin. This lack of inter-basin solidarity is difficult to understand, especially in circumstances when the Segura Basin region needs to ask the Ebro Basin for a volume unit of 1000 Mm^3/y, and the Catalans and Aragonese are asked to be understanding and generous about inter-basin water transfers. However, as highlighted in the Introduction, the west of the region (with scant demand, since it has a cold climate and it lacks a soft landscape and an abundant soil where a competitive agriculture can be developed) presents abundant resources that could be partly transferred to the east of the region in times of drought (particularly in light of the many demands, both urban and agricultural). It is therefore proposed that the first thing that needs to be done is to develop global hydric education, free from "patriotic chauvinism".

- *Optimizing natural resources, by means of spring regulation*. The regulation of the Mula Spring stands out, which was implemented through the perforation of the borehole of the Praillo (marked by the author in 1980 for the Irrigation Community of Mula), which had a continuous flow of 125 l/s. The spring has since dried up, but the piezometric level of the borehole remains stable. This spring was the natural exit of the Bullas aquifer (15 of Figure 2), which, due to its karstic nature, presented a very irregular pattern in such a way that in summer (when water is most needed) the flow was reduced and in winter the opposite happened.
- *Temporary extraction of part of the reserves in deep, unexploited aquifers*. This measure has been recommended by the author as a temporary solution until the Ebro River flow arrives, in the Jumilla-Yecla Altiplano, bearing in mind the high overexploitation suffered by the higher aquifers of this area and the great volume of reserves (1750 hm^3) that the lower aquifers present. Research evaluation boreholes have been carried out at speeds of up to 140 l/s, with perforations at depths of 500 m to 900 m, but with piezometric levels inferior to 200 m (Rodríguez-Estrella 2001), which prove this idea as a valid alternative.
- *Spatial redistribution of the extractions*. Greatest interest is focused on the overexploited aquifers, since this method would avoid the great drawdown cones, which originate near the borehole batteries (these increase the depth in the boreholes and therefore the cost), and also attract polluting substances. This was one of the recommendations from the Management Plan of the Jumilla-Villena aquifer (16 of Figure 2).
- *Use of water from rises*. By constructing dams in gullies and watercourses that flow in zones, which are permeable in an aquifer, water is collected at moments of rising and afterwards, it continues to recharge in the same place. These constructions have been proposed to the CHS, to be developed in the basin of the Quípar River (Segura River affluent).

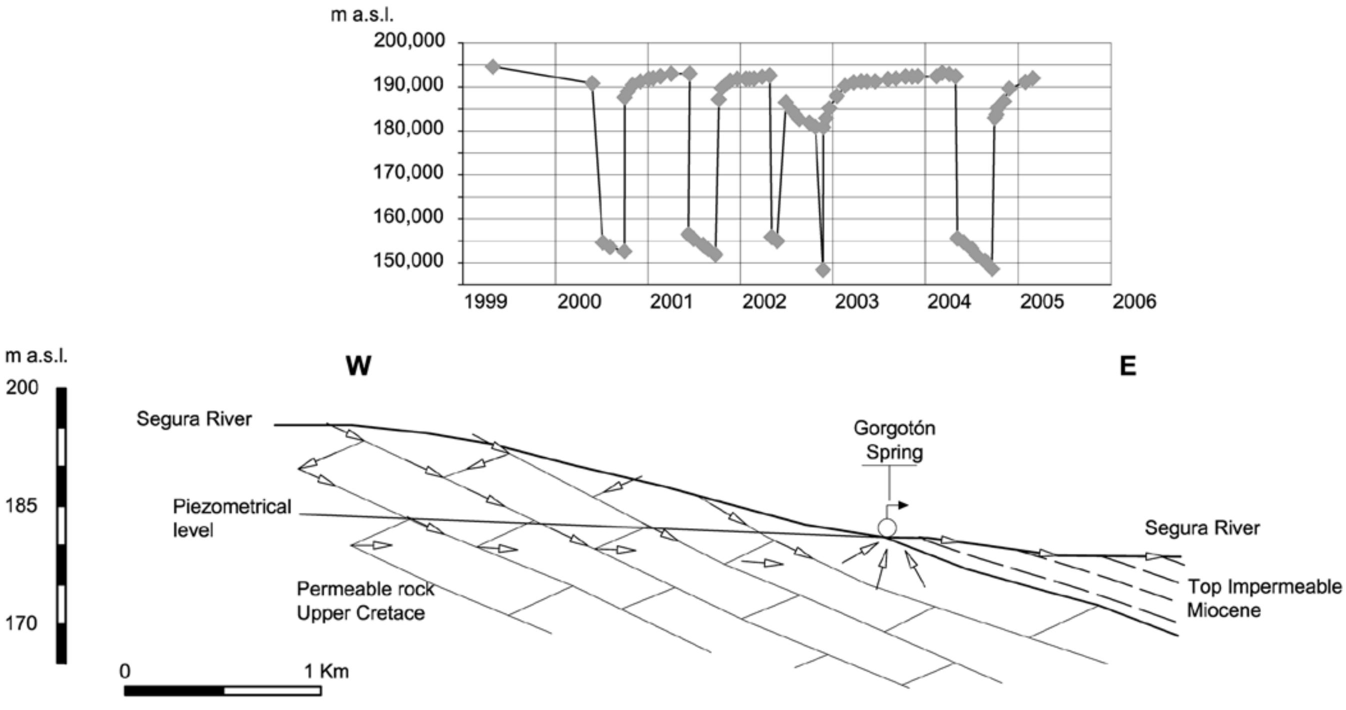

Figure 11. The piezometric evolution and hydrogeological scheme of a borehole of the Sinclinal de Calasparra aquifer, which has suffered intensive controlled exploitation.

Figura 11. *Esquema de funcionamiento hidrogeológico del acuífero del Sinclinal de Calasparra, con explotación intensiva controlada; y evolución piezométrica de uno de los sondeos.*

- *Constitution of Communities of Users of the aquifers and the design of management plans for the overexploited aquifers*. Through this development, all interest will focus on the aquifer, and it will be managed fairly; so far only one Community of Users for the Ascoy-Sopalmo aquifer has been created, though recently, those from Jumilla-Villena, Sierra de Crevillente, Alto Guadalentín, Bajo Guadalentín and Cresta del Gallo have also been declared to be overexploited, and their corresponding Management Plans are being drawn up. The creation and management of the only Community of Water-Users so far created in the Murcia Region, that of the Ascoy-Sopalmo aquifer, has played a decisive role (with its tight control on the Management Plan) in halting the overexploitation of the most over-exploited aquifer in Spain and achieving a sustainable level of exploitation.
- *Adapting the chemical quality of the water for its final use*. Excellent water quality must be maintained to cover urban demand; water of good-to-medium quality should be for irrigation purposes and water of poor quality should be used for industry. To achieve this aim, water for the general population must have different origins from water used for industry (currently they have the same origin).
- *Installing more efficient irrigation systems*. Although this is already being implemented in the whole area, there are still irrigation systems in the Segura meadows, which are irrigated by gravity and must be substituted by spraying or using sprinklers. Since the water conducting systems are in perfect condition and are being used effectively (in response to vegetative and climatic periods), a great quantity of water is conserved and, as a result, fewer extractions have to be performed. The Irrigation Communities of Mula and Cartagena Field are already computerized. Those of Guadalentín Valley and Altiplano of Jumilla-Yecla will be computerized soon.
- *Agricultural transformation*. This measure consists of the replacement of traditional crops by other crops that demand less water, especially in the Segura meadows. For example, the traditional 'maruja' melon has been replaced by the new 'tirrenia' variety; applying the same volume of water the crop production is now five times greater than before.
- *Use of wastewater for irrigation after treatment.* According to the Spanish National Hydrological Plan, 100 Mm^3/y are used in the Segura Basin for irrigation, which come from waste-water treatment plants. In the Segura basin, 95% of the waste water is treated. The root of the problem is that this treatment loses efficiency owing to the lack of maintenance since treatment plants are not 'for life' but need to be maintained regularly and kept in good repair.
- *Desalination of salty and sea water through coastal aquifers.* In the countryside of Cartagena, there are about 80 private desalinating plants, which treat salty water that proceeds from the Pliocene and High Miocene aquifers; it has more than 4 g/l of total salinity. In total, the production of water is 5 Mm^3/y. The brine is collected through a collection system of brine-ducts, located no more than 10 km from the coast (65 km net length), and they are discharged into the Albujón and Miranda watercourses, which subsequently flow into the Mar Menor.

  The Irrigation Community of Murcia Sur, of the Campo de Cartagena, has six desalinating plants, but because they are 20 km from the coast and building a brine-duct would be very expensive, the brine is eliminated by means of an injection in a borehole 748 m deep. The salty waters that come from the tertiary aquifers of the Campo de Cartagena have a salinity of between 4,000 and 6,000 mg/l, and after desalination, the brine extracted has a concentration of 15,000 mg/l; this is introduced in an unexploited aquifer formed by Triassic dolomites, which presents a higher salinity, in particular 17000 mg/l. A water product is obtained of 2.3 Mm3/y. So far, all these desalinating plants have desalinated salty water. Next we will deal with desalinating plants for seawater.

  The first desalination plant built in the Region of Murcia was that of the Irrigation Community of Mazarrón, in 1997. Using 13 boreholes (situated 2 km from the sea), they take water from the sea through the Cabezo de los Pájaros aquifer (a small aquifer situated to the south of the area). The water to be treated presents a salinity of 30 000 mg/l, so 30 Mm3/y is introduced, yielding 16 Mm3/y of water product, at a cost of €0.50/m3. This water product is mixed with other waters from the salty wells, which have a salinity of 4500 mg/l, and a water quality of 2,500 mg/l is obtained at a cost of €0.40/m3. The investment was €24M (in 1997).

  Later the desalination plant of San Pedro del Pinatar (Mar Menor) was built, which is owned by the Community of the Taibilla Channels; it began working in 2006. The desalination plant is located in San Pedro del Pinatar (province of Murcia), but collectors are situated in Pilar de la Horadada (province of Alicante). Due to the fact that a fault exists at the coast (Falla de la Costa) that hydraulically disconnects the coastal aquifers from the sea, the vertical wells built in the continent (even the beach) had negative results. It was necessary to resort to horizontal directional drilling (HDD) with the aim of tapping a sea aquifer (5 m of Tyrrhenianoolitic calcarenites) linked to an old dune rock ledge (today, an island strand called Escull) with sub-vertical fractures. Apart from the already-mentioned hydrogeological problem, there was an environmental one: the brine could not be discharged to the sea because there is a meadow of Poseidonia sea grass. It was necessary to place an outfall along the sea-bottom, 5 km long, at a depth of -30 m. The collecting is done using 20 fanned HDDs of up to 500 m in length, and pipes with a diameter of 355 mm, 50 m from the coast. The pumped flows oscillate between 100 and 140 l/s per "Neodren" and the volume of water introduced is 34.3 Mm3/y; the quantity of water-product is 23.7 Mm3/y (65 000 m3/d), which is 45% of the treated water. There are nine frames of 7 220 m3/d (Rodríguez-Estrella and Pulido, 2009).

Other desalination plants, recently built, but which are directly connected to the sea, are those of Águilas and Valdelentisco (bordering the municipalities of Cartagena and Mazarrón).

Application of many of these actions has already helped to palliate the problems of overexploitation in south-east Spain, to the point that piezometric levels in the traditionally overexploited aquifers (such as Jumilla-Villena, Quibas, and the Triassic Victorias aquifer) have been maintained or even risen over the past five years. Table 2 summarises the piezometric variations of the most seriously overexploited aquifers in the Region of Murcia (Table 2). As can be seen, the piezometric level has risen in some of these; for example in Bosque (Figure 12) and Santa Yéchar (Figure 13), they have risen by 67 and 50 m, respectively, in only five years (2008-2013). It is relevant to point out that the precipitation falling in the Segura Basin between 2005 and 2010 was above average (375 mm), and even

Aquifer	Period	Piezometric Variation (m)	Period	Piezometric Variation (m)
Burete	1991-2002	-22	2003-2013	+19
Jumilla-Villena	1970-2006	-120	2007-2013	0
Quibas	1993-2007	-25	2008-2013	+5
Bosque	1990-2004	-168	2005-2013	+67
Santa Yéchar	1989-2007	-181	2008-2013	+50
Triásico de los Victorias	1981-2006	-375	2007-2013	0
Alto Guadalentín	1975-2005	-195	2006-2013	0
Los Morales-Lorente	1980-2002	-100	2003-2013	+69

Table 2. The piezometric variation of the most seriously overexploited aquifers in the Murcia Region.
Tabla 2. *Variación piezométrica de los acuíferos más sobreexplotados de la Región de Murcia.*

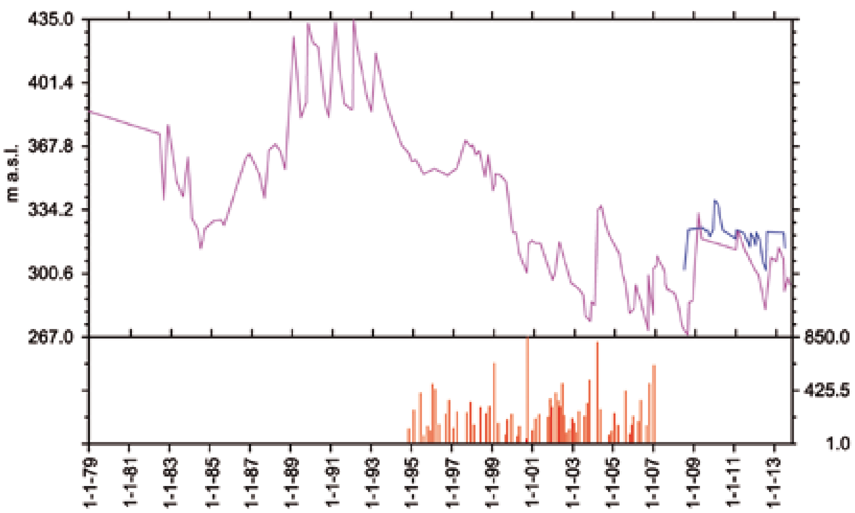

Figure 12. The piezometric variation in borehole 2537-40032 (the Bosque aquifer), according to CHS.
Figura 12. *Variación piezométrica del sondeo 2537-40032 (Acuífero Bosque). Según la CHS.*

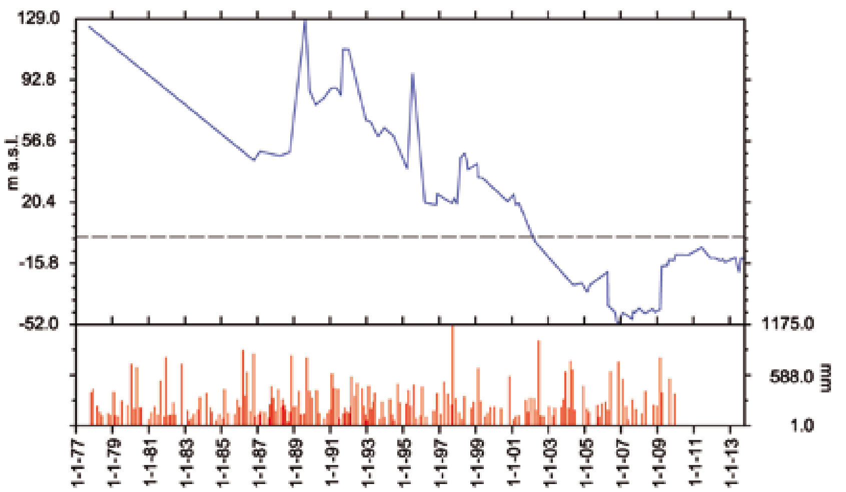

Figure 13. The piezometric variation in borehole 2638-10067 (the Santa Yéchar aquifer), according to CHS.
Figura 13. *Variación piezométrica del sondeo 2638-10067 (Acuífero Santa Yéchar). Según la CHS.*

reached 525 mm in 2010. Logically, the more it rains, the less water is abstracted from the aquifers. Nevertheless, I do not believe that the fall in abstraction was caused fundamentally by the higher rainfall, but rather by the corrective measures that have been put in place in recent years. In fact, between 2002 and 2004, there was also copious rainfall (530 mm in 2004) yet the piezometric trend in the two boreholes continued to fall. In any case, the rise in the piezometric level has a crucial effect on the cost of pumped groundwater.

Conclusions

1) Whilst the initial phase of aquifer overexploitation in the Region of Murcia brought positive effects (progressive economic development, infrastructure improvements, re-infiltration of excess irrigation water and alimentation of the aquifer, recovery of saline soils, an increase in vegetation, a concomitant increase in rainfall infiltration and the economic benefits of a change from non-irrigated to irrigated agriculture), the greatest impact of the overexploitation has been negative. These negative impacts include both direct and indirect effects. Direct impacts are the continual fall in piezometric levels, an increase in the economic cost of raising water, abandonment of wells, diminishing groundwater reserves, compaction of the terrain, compartmentalization of aquifers, a change in the physical and chemical characteristics of the groundwater, modification of river regimes, the drying out of wetlands and springs and changes in the groundwater extraction systems. The indirect effects are subsidence and ground collapse, breakage in pipelines and deterioration in roads, soil salinization and gradual desertification, etc.

2) With the aim of alleviating the hydric deficit that the Segura Basin suffers (460 Mm^3/y), and while part of the waters from the Ebro River reach the sea (10 000 Mm^3/y), a series of internal actions can be carried out within the Basin (and within the Murcia Region), such as: combined use of groundwater with surface river waters, combined use of groundwater and surface reservoir waters, inter-basin aquifer water transfer, global hydric education free from patriotic chauvinism, optimization 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 water from inundations, constitution of the Communities of Users of the aquifers and design of the Management Plans of the overexploited aquifers, adaptation of the chemical quality of the water for final use, installation of more efficient irrigation systems, agricultural transformation, use of residual waters for irrigation once depurated, desalination of salty and sea waters through coastal aquifers and computerization of irrigation surfaces, conduction and water applications.

3) The application of many of these actions has helped to palliate the problems of overexploitation in the south-east of Spain, to the extent that over the last five years in the traditionally overexploited aquifers (such as Jumilla-Villena, Quibas and the Triassic Victorias aquifer), piezometric levels have been maintained or have even risen.

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