

Groundwater problems resulting from CO₂ pollution and overexploitation in Alto Guadalentín aquifer (Murcia, Spain)

J. C. Cerón · A. Pulido-Bosch

Abstract The Alto Guadalentín detrital aquifer is both overexploited and polluted. Water conductivity ranges between 1200 and 4900 $\mu\text{S cm}^{-1}$, HCO_3^- between 1000 and 1990 mg l^{-1} , and PCO_2 between 0.041 and 1.497 bars. The temperature and chemical composition of the water show a positive thermal anomaly directly attributable to the neotectonic activity in the area. The high CO₂ content has caused the abandonment of numerous wells due to water corrosiveness which attacks pumping equipment.

Key words Hydrogeochemistry · Overexploitation · CO₂ · Abandonment of wells

Introduction

The aquifer of the Alto Guadalentín, located in the extreme southeast of the province of Murcia (Fig. 1), occupies a surface area of 236 km². Here, improved pumping equipment as well as the vigorous development of crops for exportation have notably increased water demand and thus resulted in a continuous fall in the piezometric level. The first symptoms of overexploitation appeared in 1972, but the aquifer was not legally declared provisionally overexploited until 1987.

Parallel to this development, in 1984, many wells showed the first signs of gas, composed primarily of CO₂ (80%), N₂ (14%), O₂ (2%) and, in small quantities, CH₄, H₂, and He; in addition, the N₂ content proved inversely proportional to that of CO₂ (Comunidad Autónoma de Murcia, unpublished data). Over time, the number of wells affected by CO₂ grew due to the overexploitation, and

therefore we regard the gas as a pollutant (Cerón and Pulido-Bosch 1993; Cerón and others 1994).

The local climate is Mediterranean subdesert; the average annual rainfall is 287 mm and the average annual temperature is 16.7 °C, for the period of 1966–1967 to 1989–1990 (Lorca-Cerealicultura meteorological station, situated approximately 1 km south of Lorca). The annual evapotranspiration, potential (ETP) and real (ETR), as well as the rainfall minus runoff (LLU) were calculated by the Thornthwaite method daily by the EVADIA program (Padilla and Pulido-Bosch 1986) for a retention capacity of 50, 75, and 100 mm, for the same time period and station. The ETP registered 863 mm, the ETR between 248 and 280 mm, and the LLU from 37 to 11 mm.

Within the aquifer appears a depressed area called “El Saladar”, which may have hydrochemical implications. This depression is a small endoreic basin that contained a lagoon about 40 years ago. In periods of strong flooding, the waters are retained here for a while, producing a concentration of the salts by evaporation. In addition, erosion by piping is evident, as in other areas of southeastern Spain (López-Bermúdez and Romero 1989; Martín-Penela 1994).

Geologic setting

Stratigraphic characteristics

The study area is situated in the Betic Cordilleras, in the eastern sector of Dominio de Alborán or Internal Zones (Balanyá and García-Dueñas 1987). The materials that form a great part of the relief surrounding the aquifer and its substratum (Fig. 1) are classified as: the Nevado Filabride Complex (composed of micaschists, quartzites, gneisses and marbles, from the Permian–Upper Triassic); then the Intermediate Units, represented in the area by the Sierra de Enmedio Unit (formed by slates, phillites, quartzites, recrystallized limestones, diabases, metabasites and gypsum, also from the Permian–Upper Triassic); next the Alpujarride Complex (comprised of phillites, micaschists, quartzites, sandstones, and metaconglomerates from the Palaeozoic and by limestones and dolomites from the Triassic); and finally to the Malaguide Complex (formed by sandstones, quartzites, and conglomerates from the Permian–Triassic).

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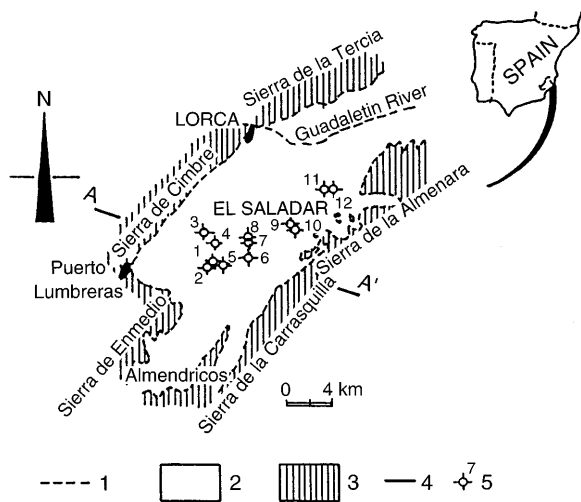


Fig. 1

Hydrogeological scheme of the Alto Guadalentín aquifer and general conditions (1 limit of the studied area; 2 Plio-Quaternary detrital aquifer; 3 border materials; 4 representative cross-section; 5 well and its number)

The materials deposited over the substratum include marl with sand conglomerates with clay and marl with gypsum, conglomerates, and calcarenites from the Miocene. Finally, over all the above, lie conglomerates, sand, silt, and clay from the Pliocene–Quaternary, which constitute the aquifer itself.

Tectonics

The study area is characterized fundamentally by the presence of successive of overthrusting units and large fracture zones that delineate interior basins (Sanz de Galdeano 1996a, b). In one of these basins, Fosa del Guadalentín, is the aquifer of Alto Guadalentín, limited on the northwest by the fault system of the Guadalentín and on the southeast by the fault system of Palomares–Almenara–Cartagena. Geophysical and petrological data, as well as data from columns taken from oil wells, reveal a crust different in nature on both sides of the fault systems of the Guadalentín–Palomares–Carboneras (Banda and Ansonrg 1980; Banda and others 1993; García-Dueñas and others 1994). These fault systems represent a certain seismic instability in the region, causing microtremors almost daily and occasional earthquakes of some intensity (Sanz de Galdeano and López-Casado 1988).

Hydrogeology

General considerations

Within the study area (Fig. 1), aquiferous behavior is presented by the quartzites and marbles of the Nevado Filabride Complex; the quartzites and gypsums of the Intermediate Units; the quartzites, sandstones, limestones,

and dolomites of the Alpujarride Complex; the sandstones, quartzites, and conglomerates of the Malaguide Complex; the conglomerates and calcarenites of the Miocene; and finally the conglomerates and sands of the Plio-Quaternary.

The depth of the piezometric level at the sampling points varies between 150 and 250 m, after initial levels of between 30 and 60 m. The transmissivity values range from 1800 m² d⁻¹ and 3600 m² d⁻¹, with a storage coefficient of 10⁻¹ to 10⁻² (IGME, unpublished data).

Geometric features

In relation to the geometry of the aquifer (Fig. 2), and based on the results of the reinterpretation of the data from electrical geophysics (Cerón 1995), the Plio-Quaternary fill has two areas of greatest sediment thickness: one, near and parallel to the northwestern border, more than 350 m thick, and another near and parallel to the southeastern border, also exceeding 350 m in thickness. By contrast, towards the centre of the aquifer the thicknesses are substantially less, registering between 200 and 300 m, and towards the northern and extreme SSW of the aquifer, the thickness of the fill is 100–200 m in the first case and 50–200 m in the second.

The marly substratum is thickest in the areas near the NW and SE edges of the aquifer (measuring more than 600 m thick and in no case detecting the metamorphic substratum). In contrast, the central zone is thinner, in general less than 300 m, and is absent altogether in some sectors. Finally, the metamorphic substratum appears, forming a central horst zone (Fig. 3), where the metamorphic substrate lies at less than 300 m in depth, as well as two areas of graben situated on both sides, near the NW and SE edges, where this substratum is not detectable.

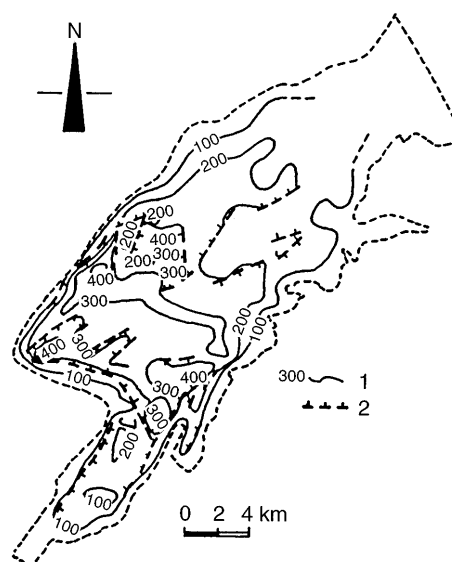


Fig. 2

Isopaches of Plio-Quaternary fill. 1 isopach (m); 2 fault deduced by geoelectrical prospecting

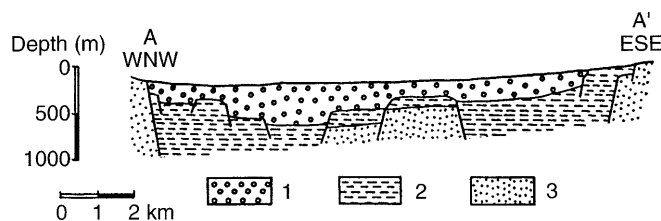


Fig. 3

Schematic hydrogeological cross section of the Alto Guadalentín aquifer. 1 Plio-Quaternary detrital aquifer; 2 Miocene substratum; 3 metamorphic substratum

Evolution of piezometric levels

Initially, the water of the aquifer was obtained in superficial zones, when the original piezometric level was quite near the surface and when there were even artesian wells. Since 1960, and especially in the last 20 years, winter agriculture has undergone intense development of enormous economic value. Concomitantly, water demand rose substantially, with a considerable increase in exploitation of this resource in the zone, resulting in the overexploitation of the aquifer. The exploitation of the aquifer was calculated at between $24 \text{ hm}^3 \text{ y}^{-1}$ (1973) and $69 \text{ hm}^3 \text{ y}^{-1}$ (1987), rates that lead to a continual fall in the piezometric level (Comunidad Autónoma de Murcia, unpublished data). Table 1 shows the mean values of the fall in the piezometric level in the aquifer. Similarly, Fig. 4 shows the drops for the periods 1975–1984, 1984–1989, and 1989–1992.

Parallel to the problem of overexploitation, many of the wells began to show signs of contamination by gas, principally CO_2 , which originated from, and continues to be produced by, a combination of serious problems related to the pumping and use of the water.

Table 1

Mean values for drawdown level of the aquifer

Sector	Mean drawdown (m yr^{-1})	Period	Source
Central	2.5	1973–1976	IGME-IARA (1978)
	4.5	1976–1983	Com. Aut. Murcia (1988)
	10	1984–1985	Com. Aut. Murcia (1988)
	4–7	1986–1989	Rodríguez-Estrella and others (1989)
	2–3	1989–1992	Cerón (1995)
Western	1–1.5	1973–1976	IGME-IARA (1978)
	4–5	1976–1983	Com. Aut. Murcia (1988)
	12	1986–1989	Rodríguez-Estrella and others (1989)
	4–6	1989–1992	Cerón (1995)
Eastern	2.5	1973–1976	IGME-IARA (1978)
	4.5	1976–1983	Com. Aut. Murcia (1988)
	1	1986–1987	Rodríguez-Estrella and others (1989)
	1.5–2.5	1989–1992	Cerón (1995)

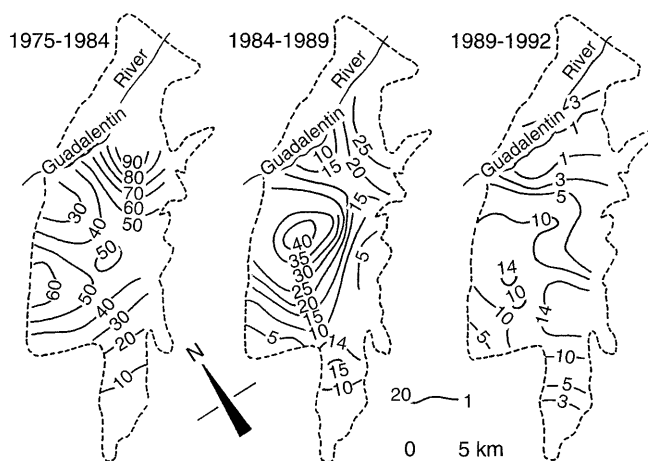


Fig. 4

Maps of drawdown values of the aquifer. 1 curve of equal drawdown (m)

During the period of this study (1989–1992), a general reduction was recorded in the fall of the piezometric level, which, in some wells, stabilized and even reversed the downward trend. This change was due to the decreased pumping and/or abandonment of wells as a result of the poor water quality – primarily in reaction to salinization and CO_2 content – as well as a greater source of water apart from the aquifer (water transfer from Tajo River to Segura River). Nevertheless, a high rate of exploitation continued in the western sector of the aquifer, where piezometric drops measured $4\text{--}6 \text{ m yr}^{-1}$, with respect to the central sectors ($2\text{--}3 \text{ m yr}^{-1}$) and the eastern sector ($1.5\text{--}2.5 \text{ m yr}^{-1}$). At present, the piezometric level registers between 150 and 250 m in depth.

The hydrologic balance (Table 2) for the period 1966–1990 illustrates the precarious situation of the aquifer due to the serious deficit between input and output. This deficit is difficult to eliminate, not only because of the aridity of the climate and the impossibility of bringing more external resources to the aquifer, but also because of the need in this arid environment to continue pumping for agricultural demand, the major source of income in the region.

Physicochemical characteristics

General aspects

The waters in general have temperatures of $23\text{--}31^\circ\text{C}$, a pH between 6.01 and 7.07, high conductivity of 1120 and $4900 \mu\text{mhos cm}^{-1}$, PCO_2 between 0.041 and 1.497 bars, and HCO_3^- between 495 and 1890 mg l^{-1} (Table 3). These waters are calcium–magnesium sulfate–carbonate–chloride and often sodium types. There is a direct relationship between the higher concentration in ions and the waters coming from the substratum, through Miocene rocks, where the evaporites such as sulfate–chloride salts

Table 2
Hydrologic balances of the Alto Guadalentín aquifer^a

	Dry year	Average year	Wet year
Influxes			
I _{ES}	2	7	21
I _D	0	6	21
R _R	5	5	5
A _P	?	?	?
Total	7	18	47
Outfluxes			
S _{BN}	25+?	25+?	25+?
S _L	3–5	3–5	3–5
Total	28–30	28–30	28–30
RV	–21––23	–10––12	19–17

^a I_{ES}: runoff infiltration; I_D: direct infiltration from rain; R_R: irrigation return; A_P: input of deep origin (substratum); S_{BN}: net output by pumping; S_L: hidden lateral output; R_V: reserve variation – difference between input and output. Values in hm³ yr⁻¹

dissolve. To a lesser extent, agricultural pollution also contributes to the salinity. In addition, a proportion of the water mineralization results from the dissolution of soil salts and salt deposits of Saladar.

With regard to the water quality of the aquifer for irrigation, the water in general carries the risk of soil saliniza-

tion. The risk of alkalization, meanwhile, is medium to high, making a good washing of the soil necessary where this water is used (in some cases this is difficult due to the lack of any other type of water). Where high values of sodium ions are reached, it is important to take corrective measures.

Aspects of CO₂ in water

The CO₂ in the Alto Guadalentín detrital aquifer is the result of gas migrating through two principal routes: the great tectonic systems (fault systems of the Alto Guadalentín), which affect the materials situated underneath the aquifer, a reflection of the neotectonics active in the area; and through the wells that perforate the metamorphic substratum.

The relatively recent presence of CO₂ in certain areas of the aquifer, which never before had had gas, derives basically from overexploitation. This has caused a marked fall in the piezometric level, which has decreased the hydrostatic pressure to less than the PCO₂, allowing the ascent of the gas from deep zones of the aquifer towards the surface (Rodríguez-Estrella and others 1989). In reality, the greatest CO₂ contents in the waters are registered in the sectors where the metamorphic substratum is shallow. This situation, brought about by human activity, prompts us to consider this CO₂ a contaminant (Cerón and Pulido-Bosch 1993).

At the same time as this process is occurring, the wells are pumping water from the deepest zones (and thus

Table 3
Physicochemical characteristics mainly from several points of the detrital aquifer^a

Point	T (°C)	pH	C (μS cm ⁻¹ at 25 °C)	PCO ₂ (bars)	Ions (mg l ⁻¹)								
					Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SiO ₂	NO ₃ ⁻
1*	29.3	6.12	2840	1.225	400	1185	1890	601	297	163	65	31	0.3
2*	29.8	6.19	3110	0.972	400	1318	1760	585	354	165	65	28	0.5
3*	30.5	7.07	1200	0.044	220	300	540	157	77	135	61	24	5.0
4*	30.2	6.31	1590	0.455	200	380	1000	232	143	133	58	30	7.5
5*	29.1	6.08	3500	1.237	370	1310	1700	597	336	187	66	29	0.1
6*	25.2	6.21	3180	0.843	430	1053	1650	500	311	193	64	36	0.5
7*	29.6	6.13	2140	0.901	450	260	1350	364	184	133	62	23	6.0
8*	28.7	6.38	2710	0.369	743	405	1000	435	193	172	61	22	10.0
9*	26.9	6.60	3190	0.214	595	1010	1000	441	277	278	59	26	12.0
10*	26.8	6.54	3100	0.221	615	875	885	398	239	255	62	21	10.0
11*	24.5	6.12	4310	1.018	798	1800	1700	722	521	344	75	17	2.8
12*	23.1	6.41	4130	0.255	860	1134	800	405	310	384	63	22	9.0
1**	29.3	6.01	2830	1.497	426	1283	1890	667	244	181	67	28	0.1
3**	30.2	7.07	1120	0.041	191	205	495	113	58	147	60	23	6.7
4**	28.7	6.62	1820	0.224	190	355	1015	211	117	142	59	29	9.5
5**	29.7	6.07	2990	1.167	355	1298	1586	570	260	191	67	26	0.2
6**	28.5	6.16	3020	0.783	426	1024	1305	470	230	190	70	31	0.7
7**	29.2	6.12	1860	0.677	426	225	976	275	147	162	68	25	7.2
8**	28.4	6.44	2840	0.261	781	437	810	377	170	221	67	23	12.1
9**	26.0	6.78	3350	0.143	568	925	1010	393	216	349	63	27	15.2
10**	26.4	6.69	3120	0.141	639	703	800	341	198	318	66	24	13.5
11**	24.8	6.16	4860	0.664	710	1631	1183	521	389	406	83	25	3.4
12**	24.0	6.51	4590	0.216	923	1223	854	486	268	502	69	25	10.9

^a * August 1991; ** November 1991

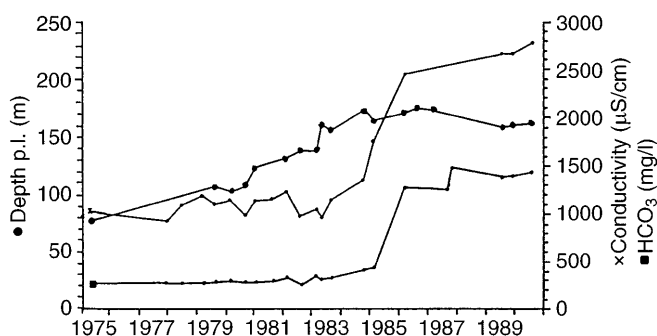


Fig. 5

Time course of piezometric level depth, water conductivity, and bicarbonate ion content

those with the greatest salinity); this situation explains why the CO_2 increases with other salt contents. In this sense, Fig. 5 represents the evolution over time in the content of the bicarbonate ion, in conductivity, and in the piezometric level at a well (very close to aquifer point 4), which was abandoned in 1990 for failing to be economically profitable.

Thus, a notable concentration in the bicarbonate ion is evident when the depth of the water exceeds 150 m. Similarly, Table 4 shows the chemical composition of the waters of the same well between 1975 and 1990. The bicarbonate ion content and conductivity rose substantially between 1984 and 1986.

In addition, at the aquifer point, the CO_2 content stabilized in the water at a certain depth, due to the hydrostatic pressure being greater than the PCO_2 . This point is also situated very near a well that had to be closed in 1990 for its high CO_2 content (more than 2100 mg l^{-1} of bicarbonates). The well waters, although containing high concentrations of bicarbonate, did not show obvious signs of the rise in CO_2 contamination until the deepening of the pump system into the well. In the water, gas bubbles were visible, indicating the increase in CO_2 , confirmed later by analyses which showed a rise in the bicarbonate content (of approximately 250 mg l^{-1}). In this way, falling piezometric levels in the zones with gas,

more pronounced in those areas with greater exploitation, require a deeper pumping, with the consequent worsening the water quality. The solution to this problem is to regulate the volume pumped to avoid a fall in the piezometric level.

Problems caused by CO_2 in water

The principal negative repercussions of the presence of CO_2 in the water appear in the pumping equipment and the casing of the wells and pipes. That is, there is rapid corrosion of the metal parts, precipitation of carbonates, loss of pumping volume (reduced yield with occasionally more gas than water, so that water does not reach the surface), and the breakage of pressure pipes from cavitation caused by excess pressure due to gas accumulations in the pipes (Rodríguez-Estrella and others 1989).

In addition, some wells and pumps are seriously damaged by gas-lift, a process that occurs only when a highly soluble gas develops in the water in major quantities. In this situation, the content of the dissolved gas increases with pressure and, as a consequence, during the rise of the water with CO_2 from deep zones, part of the dissolved gas can be liberated in a liquid phase, transforming into an emulsion of liquid and gas with a very low density that favors the ascent of the water. As the CO_2 - H_2O -carbonate reactions are reversible, all the springs and pumping of carbonated waters can be affected by this phenomenon, producing a precipitation of carbonates near the surface. This process is invariably associated with thermalism, given that the high contents in CO_2 come essentially from deep sources (Bakalowicz 1986).

With reference to the effects on the soil and plants by irrigation with these waters, some crops have no negative reaction, while others are quite sensitive. A deposit of iron carbonate develops in the soils, impeding aeration in the root zone, and the salts precipitated in the soil give rise to compounds such as sodium bicarbonate that are toxic to plants (Rodríguez-Estrella and others 1989).

Table 4

Time course of physicochemical parameters^a

Date	Cond. ($\mu\text{S cm}^{-1}$)	Ions (mg l^{-1})							
		Cl^-	SO_4^{2-}	HCO_3^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	NO_3^-
29/05/75 ^a	1050	139	130	283	90	40	94	2	
20/04/80 ^a	1300	131	158	317	106	52	76		22
06/11/84 ^a	1375	106	180	421	122	49	103	4	
25/03/85 ^a	1760	192	210	445	180	48	138	8	28
20/04/86 ^a	2456	160	664	1270	295	192	165	5	3
13/09/89	2690	135	502	1389	184	258	98	41	4
30/01/90	2690	120	498	1405	195	260	102	40	10
15/09/90	2790	140	535	1438	235	284	123	46	13

^a IGME

In short, there are heavy economic costs of CO₂ and thus of overexploitation of the aquifer (not counting the salinization of the water). Yield reduction (frequently 30%), equipment breakdowns (generally every 3 months and causing the abandonment of many wells), and increased pumping costs (volumes extracted contain a minimum of 30% gas) have brought minimum losses since 1984 to approximately 5 million dollars, which increases to 7 or 8 million dollars when adding in the costs of electric installation, converters, and pumps (Comunidad Autónoma de Murcia, unpublished data).

Final considerations

The presence of CO₂ in the Alto Guadalentín detrital aquifer is probably the product of migration from underlying materials. This migration appears to be related to wells that perforate the aquifer substratum and to the major tectonic faults affecting the area. The appearance of CO₂ in wells formerly without this gas can be attributed to overexploitation. At the same time as this process occurs, the wells draw water from the deepest zones with greater salinity. The CO₂ in the water has brought about losses of 7–8 million dollars and thus represents serious economic damage in the region, which is primarily agricultural and is suffering from the extreme drought of the last few years.

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