QUANTITY AND QUALITY OF GROUNDWATER IN THE CAMPO DE DALIAS (ALMERIA, SE SPAIN)

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ABSTRACT

The Campo de Dalias is the most economically important agricultural area in the whole of the Province of Almería. A benign climate combined with the expertise of the market gardeners and their intensive cultivation in plastic hot-houses of out-of-season fruit and vegetables has turned a stony wasteland into an area of great productivity. The main water supply comes from a series of wells drilled into the subterranean aquifers running through the local rocks, a geometrically complex succession of Triassic limestones and dolomites, Miocene conglomerates and calcareous sandstones, Pliocene calcarenites and Quaternary gravels, sands and silts. The annual influx into the aquifers has been calculated as being around 50 hm³, while at the present day more than 100 hm³ are being taken out during the same period. This over-exploitation of the resources is causing an inexorable descent in the water table, which is leading to marine intrusion in those aquifers nearest the sea. The main aquifer-bearing units are Balanegra and Aguadulce, composed essentially of Triassic, Alpujarride carbonates, and the Balerma-Las Marinas unit, made up of Pliocene calcarenites. In the water from some of the wells in the Aguadulce unit more than 10,000 microS/cm have been measured at some distance from the coast, while in the Balanegra unit there are a large number of conoids below sea level, although marine intrusion is at present limited to a fairly narrow coastal strip.

KEYWORDS

Semi-arid region; overexploitation; salt water intrusion; structural conditions.

INTRODUCTION

The Campo de Dalias is situated very near the Southwestern extreme of the Province of Almería, between the versant basins of the Adra and Andarax rivers. It occupies a surface of nearly 330 km². The Northern limit is made up of the foothills of the Sierra de Gador, while the remaining borders are occupied by the Mediterranean Sea (Fig. 1).

The area presents a relatively smooth relief, included between 300 metres above sea level and sea level itself: it records a continual slope towards the sea, broken by the existence of some steep slopes which are more or less abrupt and by a series of closed forms, some of which are of great width like the one which exists in the surroundings of the Las Norias-Mojonera.

There are a series of villages in the Campo, in many of which the number of inhabitants has notably increased, due in a great extent to the economic boom which the agriculture of the area has enjoyed. Moreover some of the villages are touristic and the population in the summer increases considerably.

The economic boom in the Province of Almería has come about in a great extent as a result of the agricultural activity of the Campo de Dalias. The climatic conditions (semi-arid) of the area which have permitted the cultivation of numerous horticultural products at times when the...
market has not been well supplied, have contributed to this boom thanks to the great number of hours of sunshine and the ingenuity and effort of the farmers in Almeria.

The irrigated surface in the Campo de Dalias, according to data of the Chambers of Agriculture, has more than doubled between 1961 and 1981. During this period a notable qualitative change has also taken place, in the cultivation technique as well as in the intensity of the same; in fact, the surface cultivated with cereals, leguminous, fodder, etc., has practically disappeared since the fruit and vegetables have increased. The cultivations are usually done by covering them with sand, in a large surface under plastic and we evolve towards irrigation techniques which economize on water to a maximum (dripping).

The growth of the cultivated surface has been continual, in the greenhouses as well as in the use of the sand covering method, estimating that currently the cultivated hectares reach 14,000. We can say that it has been this intense agrarian activity which has acted as the impulse of the economic development in Almeria, where the final agrarian production between 1972 and 1980, which was 35,000 millions, has been quintupled. Nevertheless, without doubt the lack of water is the greatest limitation to the agricultural growth.

On the other hand, there has been a notable increase in the population which competes with the agricultural demand, with respect to the land occupation on one hand and the water demand on the other. The 24,000 inhabitants when the census was taken in 1960, increased to 40,860 in 1970 and 64,000 in 1981. We estimate that the current stable population reaches 85,000 and is doubled in the summer months.

The industry developed in the Campo is scarce and is generally narrowly related to the elaboration of the agricultural product and/or to the materials which are necessary for the agricultural activities. No large industry which requires an important flow of water is known.

THE GEOLOGICAL FRAME

The outcrop land can be grouped into two large sets: prerogenic materials and postorogenic materials. Two different units occur in the first group: units of Lujar nappe (or Gador); and units of Murtas nappe (Felix). In the Lujar nappe, a member of phyllites and quartzites is differentiated, on which an important carbonated series which surpasses the thickness of thousands of metres, rests.

In the Murtas nappe materials, like the Gador nappe, there is a lowermost metapelithic member and another upper carbonated serie. The lowermost member is made up of phyllites, shales and purple and green coloured quartzites. Some intercalations of yellowy calcoeschists are present. The upper carbonated member presents much less thickness than its equivalent in Lujar (normally less than 100 m). It deals with dolomites, recrystalized and frequently ground limestones. Similar ages are assigned to the equivalent members of Gador (Permowerfenian to the metapeli tes and middle-upper Trias to the carbonated serie). These materials occur or suboccur in the Eastern half of the area being studied (Fig. 1).

Deposits which are included between the upper Triassic and the Miocene ages are not known. The materials of the late Miocene occur along the Northern border of the Campo, on the limestones and dolomites as well as on the phyllites and quartzites of both units; they appear locally on conglomerates of boulders of lava and on volcanic rock. These volcanic rocks should be of the Tortonian age as they are covered by calcarenites of the late Tortonian age. The Tortonian-Andalucian series is made up of biodolomycrites or biomicrites with quartz pebbles, metamorphic rocks and many remains of scarcely rounded organisms. The thickness of the Miocene set is more than 100 m, although this decreases in an appreciable manner towards the West. For bore-hole data the existence of a lowermost conglomerate is known, on which a marine marly formation of a very variable thickness, which could be more than 700 m thick, was deposited. These marls occur in some sectors of the Southern border of the Campo. Calcareites which culminate the formation begin to appear on the top; they surpass 100 m in thickness and make up the outcrop relief on the whole Southern half of the Campo.

The materials of the Quaternary age are widely represented by very diverse facies. The materials which present the greatest interest are the debris cones which are developed on the side of the Sierra de Gador. Made up of very heterometrical angular pebbles, they are locally covered with a crust. They reach a thickness of more than 150 m. Moreover, older Quaternary deposits exist, marine ones; some authors differentiate up to four marine episodes represented by different lithologies in the sector.
Red clay-like mud with some quartz pebbles occurs in the continental facies as well as the aforementioned debris cones. Apart from the sediments mentioned there are others with scarce development; it deals with slimy and muddy deposits related to the marsh, more or less stabilized dunes and beach sediments which border the current littoral.

As far as the different tectonic stages which have affected the area are concerned, the most important paroxysm referring to structural consequences, is that which caused the transfer of the stratum, Murtas over Lujar. The "neotectonic" deformations are those which contribute most to giving the area its current disposition; this involves the stages of fracturing, tilting and heaving; Fourniguet (1977) even describes small quaternary folds. After the Late Miocene, the high bottom of Gador fractures according to the dominating N 70 E direction. It concerns normal but very uneven faults which produce a series of compartments within the basin; the horst of Guardias Viejas and the graben which occupies the whole central sector of the Campo (Fig. 2), stand out.

After this distensive period, the Pliocene transgression is produced, with large accumulations of marine deposits; after the late Pliocene regression, the abrasion plain which is generated is affected by the faults from which we can differentiate at least three generations: faults of N 25 E or N-S direction which produce steep slopes, some of which are very notable; faults of E-W direction which are responsible for the existence of a large arid central basin; and faults with a N 120 E direction which would be the most recent period of fracturing affecting the Quaternary marine sediments and even the debris cones.

**HYDROGEOLOGICAL CHARACTERISTICS**

Within the units of Lujar nappe (or Gador) the base of the carbonated series would have aquiclude behavior; the carbonated series of Lujar nappe -limestone and dolomites- has aquiferous behavior due to fissuration and karstification. The materials of units of Felix have a construction similar to those of the Gador, that is to say, a lowermost member of aquiclude behavior, and a carbonated member with aquiferous behavior, with high permeability, although the thickness in this case is less than that of Gador.
Fig. 2. Schematic cross-sections of the Campo de Dalias; particular position is indicated in figure 1.

As far as the postorogenic materials are concerned, from the oldest to the most modern, we have the marls with gypsum and conglomerates, recognized in some deep holes; the most distal facies -those which have a higher fraction of clay content- can be considered as having aquiclude behavior following on to aquitard and poor aquiferous as we approach the edge of the basin. The calcarenitic deposits of this same period have aquiferous behavior with intergranular voids, fissuration and karstification which contribute to increasing its permeability. The conglomerates of boulders of volcanic rock and volcanic rock itself are found with regard to those deposits; in accordance with the pumping-test data they behave as poor aquifers.

With respect to the Pliocene materials, the lowermost conglomerate -whose geometry is unknown- would have aquiferous behavior, while the thickness marly marine series behaves as aquiclude; nevertheless, in the sectors which are not very thick, where there is also a fraction of sand, we can establish a flow to its bias (aquitard) a function of the vertical permeability and of the difference of the hydraulic charge between the infra and supradjacent aquiferous formations. The calcarenites which culminate the Pliocene series have aquiferous behavior.

The Quaternary gravels with sands and other finer elements which make up the large debris cones which cover the side of the Sierra de Gador, have aquiferous behavior, are highly permeable and have intergranular porosity. The materials corresponding to the Quaternary marine episodes, due to their corresponding to their scarce development, are not of great hydrogeological interest; their behavior is variable between poor aquiferous and aquitard, depending on the proportion of fine elements.

In accordance with the structure of the area and the information provided by the inventory of almost 1200 aquiferous points within the Campo, we have differentiated three hydrogeological units (Fig. 3).

- Balerma-Las Marinas, which occupies the greater part of the area studied, from Balerma to Las Marinas. It is essentially integrated by the Pliocene calcarenites.

- Balanegra, which occupies the surroundings of the locality which justifies its name. It is
Quantity and quality of groundwater

Fig. 3. Differentiated hydrogeological units in the Campo de Dalias. 1: Aguadulce; 2: Balerma-Las Marinas; 3: Balanegra.

essentially made up of carbonated Alpujarride materials, although they locally include Miocene and Pliocene land.

- Aguadulce, situated in the Eastern extreme of the Campo; it is integrated by the Alpujarride dolomites, calcarenites and Miocene volcanic rocks, calcarenites with episodes of sandy marls of the Pliocene age and Quaternary materials.

The Balerma-Las Marinas Units

This unit is that which occupies the largest extension in the whole Campo, with about 225 km$^2$ of outcrop. It extends all along the littoral plain, and only the Northeastern plain and the piedmont fringe are left outside. The largest part of the agricultural activity is situated in this aquiferous area. The thickness of the Pliocene materials, which this unit especially integrates, decreases from North to South, at the same time as the proportion of the terrigenous elements increases. The data of numerous pumping tests (IGME, 1982) show the great spatial variability of the transmissivity, with values which reach 1800 m$^2$/day in the central sector and 120 m$^2$/day in the Western sector.

The most peculiar hydrogeological characteristic of this unit refers to the spatial and temporal piezometric evolution; in fact practically the whole area is found below sea level and the temporary piezometric evolutions show the existence of a generalized tendency to increase or to stabilization (Thauvin, 1986). The bad natural quality of its waters (Pulido Bosch et al., 1989 a) and the fact that the majority of the irrigations were carried out on its surface, would justify this answer.

The exploitation of groundwater in this unit reaches an average value of 15 Hm$^3$/year; small local exploitation eventually creates notable conoids of depletion (Pulido Bosch et al., 1989 b). The total average influx is estimated at 18-24 Hm$^3$/year.

The Balanegra unit

This hydrogeological unit occupies the Western half of the Campo and has the aquiferous bearing units of Balerma-Las Marinas in the bottom part, and is separated from it by the Pliocene marls which act as the confining top. The aquiferous material essentially corresponds to the Gador dolomites, although the Miocene calcarenites can also participate in the storage. The impermeable substratum is considered to be integrated by the lowermost metapelites of the Gador nappe (Lujar). It occupies 195 km$^2$ of which less than half are found to be confined under the Pliocene marls. The Northern and Western limits of the unit which are naturally impermeable, are made up of the lowermost metapelites of the nappe; the Southern limit has to be the sea, although the sea is not in contact with the aquifers all along the coast, but only across the tectonic scale of Balsanueva ("Escama de Balsanueva; Fig. 1).
Values included between 15,000 and 22,000 m²/day have been obtained with respect to the hydraulic parameters of the system. The storage coefficient in the calcarenites, in free aquiferous conditions, can be included between 15 and 20 % (IGME, 1982).

The existence of values of the piezometric level below sea level in this aquiferous area is a fact that was stated in the low waters of 1978; from that year on, the descents are continual of around 0.75-1 m/year, which is the result of the existence of a volume of extractions superior to the influx. In 1989, there were several conoids with their piezometric level more than 10 m below sea level. While the average influxes are estimated around 15 Hm³/year, the extractions double the said flow (Fig. 4).

The Aguadulce unit

This hydrogeological unit is the most tectonically complicated. Together with the existence of the greatest part of the aquiferous materials present in the Campo, several aquiferous formations appear in vertical cuts separated by other formations with low permeability, thus causing a real multilayer aquifer; however, some of the formations can be pinched out in a more or less abrupt way.

So much lithological variety within the aquiferous formations logically has its incidence in the values of the hydraulic parameters. We have obtained values included between 5,000 and 17,000 m²/day in the Gador dolomites. Very uneven results which cover a range which varies from 6,000 in the Miocene calcarenites to 200 m²/day in plioquaternary materials are obtained in the remaining materials.

As in the previous unit, the piezometric materials have descended continually since 1973, when values below sea level were recorded as from 1977; the most recent data show that the largest part of the surface was piezometrically submitted in the aquiferous matter which is found below sea level, thus reflecting the state of overexploitation to which it is subjected (Fig.4). In fact, while the average extractions are approximately 50 Hm³/year, the influxes are around 15 Hm³/year.

EXPLOITATION AND QUALITY

The flagrant lack of balance that exists between the pumpings and the the influx should be reflected in the physical-chemical characteristics of the waters, and this is why in the middle of 1986 some control networks were selected with biannual, monthly and daily sampling periodicity, and later optimized using the "cross validation" method (Pulido Bosch et al., 1988 b); the data obtained enable us to make the following considerations.

The Balerna-Las Marinas unit

In this unit, in spite of the fact that overexploitation does not exist, the waters present a very poor natural quality, as can be seen in figure 5 which shows the spatial variation of the values of the conductivity. Local values which are superior to 7,000 microS/cm are recorded, and many of the samples present sodium-chloride compound facies (Fig. 6). We have interpreted...
all this as being due to the existence of saturated sediments in salt water which have been trapped in sunken blocks which have been generated in the recent tectonic activity. In figure 7 we show the temporary evolution of the conductivity in one of the control wells, showing a certain resistance to the increase, although in a very subdued manner.

The Balanegra Unit

This unit presents a clear lack of balance concerning the influx and extraction (Fig. 4), with pumpings which are very much superior to the influxes. However, a notable deterioration of the quality of the waters as a result of an eventual marine intrusion have not been detected during the period of control (Fig. 8); the interpretation of this occurrence has to be looked for in the structure of the unit along the marine edge; in fact, the data points to the absence of hydraulic connection, which is essentially due to the existence of the metapelitic base of Gador throughout the contact, except in the tectonic scale of Balsanueva where the average values indicate a high percentage of sea water in the mixture.
Although the hydrogeological facies which are present (Fig. 9) cover a wide spectrum, those of calcium and/or magnesium biocarbonated facies dominate, although with a complete gradation to the sodium chlorides. The temporary evolution of the conductivity in one of the controlled points is shown in the figure 9.

The Aguadulce unit

With respect to the lack of balance in influx/extraction, something similar to what happens in the Balanegra unit happens here, although in this case the hydraulic connection with the sea is much more clear and evident. In fact, all along the sectors submitted to intense pumpings, high levels of conductivity are recorded (more than 10,000 microS/cm), which at the same time present the lowest values in the piezometric levels (Fig. 8).
DISCUSSION

The Campo de Dalias makes up one of the existing multiple examples throughout the world of how the scarcity of water acts as a limiting element in economic development; the exploitation of the groundwaters has enabled us to convert the waste ground of a region into an area of great economic strength. However the price paid has been the partial deterioration of the quality of the waters and a future uncertainty as to whether alternative sources of water supply will be found.
A channel which brings water from the Beninar reservoir in the River Adra, a few kilometres to the West of the Campo, has been put into operation; this reservoir will supply the drinking water to the town of Almeria which at the moment is supplied by water of the Campo, and so the extractions will also be reduced. The attempts on the part of the Administration to carry out transfers of waters from other basins are confronted with the systematic opposition of the users in the said areas.

Some of the new touristic installations already count on supply systems which consist of desalinating the sea water. Another element which should equally be considered consists of using purified residual waters in irrigation. Finally, and as a recent study has shown (IARA, 1989), the adequate conservation of the distribution network of irrigation waters and the correct management of liquid can permit the saving of up to 20% of the total irrigation necessities. If the resources were still insufficient, we would have to opt for reducing the demand of the corresponding fraction with the resulting socioeconomic influence.

Another thing which can be considered is that we think it is interesting to point out the importance that the structure of a hydrogeological unit has in the potential deterioration processes of the quality of the waters; such is the case in the Balanegra unit where there is an exploitation similar to that of Aguadulce; in the former there are no notable physical-chemical indications of marine intrusion, while in the latter the most productive sectors have had to be partially abandoned and have had to locate new sites to situate the wells which have been abandoned (Pulido Bosch et al., 1988 a). The existence of a practically impermeable barrier between the aquifers and the sea in the Balanegra unit is what is responsible for this difference.

ACKNOWLEDGEMENTS

To IARA as the organisation which has co-financed the investigation; the works of research have been carried out likewise in the framework of the project PB087-0245 of the CICYT.

REFERENCES


