Intensive agriculture, wetlands, quarries and water management. A case study (Campo de Dalias, SE Spain)

A. Pulido-Bosch · P. Pulido-Leboeuf · L. Molina-Sánchez · A. Vallejos · W. Martin-Rosales

Abstract The intensive agricultural activities that have developed over the last 50 years in the Campo de Dalias (Almeria region) have required large quantities of gravel and clay as the basic materials for the substrate over which crops are raised. With this motive, numerous gravel pits have been opened that have extracted several million cubic metres of material in recent years. Similar quantities of clay have been extracted from the distal sectors of the alluvial fans that descend from the Sierra de Gador, and from within a large endoreic basin. In the latter quarries, some wetlands have developed, probably because of the rise in the water-table level in the aquifer over which they lie. The gravel pits are situated in the apical sectors of the alluvial fans, overlying hydrogeological units that are widely overexploited. For this reason the gravel pits could be used for artificial recharge; in addition to increasing the availability of water in the aquifer, the risk of catastrophic flooding would also be reduced.

Introduction

Today, ~20,000 ha of extra-early market produce is grown in greenhouses in the Campo de Dalias. Their economic significance is so great that they constitute the principal generator of development in the Almería region. It is estimated that the economic activity related to this extra-early agriculture accounts for more than US$ 1.5 billion per year. These agricultural activities have been achieved at high environmental cost (the generation of large quantities of plastic sheeting and agricultural wastes, the contamination of aquifers etc.) and because of the enormous efforts on the part of farmers and administrators, which are founded on the use of groundwater that is basically derived from infiltration in the Sierra de Gador.

Given that the average precipitation in the Campo de Dalias only slightly exceeds 200 mm a year, the exploitation of the aquifers that form this hydrogeological system has been much greater than their recharge. The total surface area of the Campo de Dalias is ~320 km^2; the southern edge of the Sierra de Gador covers an area similar to that cited for the Campo. Fifty-five *ramblas* (ephemeral stream beds) that drain areas of variable size, of between 54.1 and 1.1 km^2, run down from the Sierra de Gador, and, of these, only five at each end are able to discharge directly to the sea. The rest flow into the central part of the Campo de Dalias, which, for tectonic reasons, constitutes an endoreic basin (Fig. 1).

With regard to the lithostratigraphy, the oldest rocks outcropping within the area are metapelites and carbonates that belong to the Alpujarride Units, and they cover almost all of the southern edge of the Sierra de Gador (Fig. 2). These materials belong to two tectonic units, namely Gador and Felix, and the first of these is much more widely-represented than the Felix unit. It is worth highlighting that the Gador carbonate rocks can be up to 1000 m thick, although there may be intercalations of calcoschists and marly limestones. Over the Alpujarride materials, which are of Permian and Triassic age, lie Miocene materials that consist of calcarenites in the outcropping sectors, and marls with gypsum beneath the Plio-quaternary fill. Locally, the Miocene strata are represented by conglomerates comprised of large boulders of volcanic rock. The Pliocene materials are widely developed throughout the whole of the Campo de Dalias (Aguirre 1999); the base is comprised of up to 700 m of blue marls, with sandy bands occurring with greater frequency towards the top of the series. The Pliocene series culminates with a calcarenite member with a maximum thickness of 120 m. The Quaternary sediments are represented along the entire southern edge of the sierra, and are comprised of large alluvial fans that locally exceed 150 m in thickness. The deposits of both former and contemporary beaches, together with the fine terrains of the distal parts of the large alluvial fans, complete the materials that occupy the Campo de Dalias.

These formations have a complex tectonic structure that confers a great complexity to the geometry of the three

Revision received: 19 November 1999
Accepted: 28 December 1999

A. Pulido-Bosch (✉) · P. Pulido-Leboeuf · L. Molina-Sánchez · A. Vallejos · W. Martin-Rosales
Department of Hydrogeology, University of Almeria, Spain
e-mail: apulido@ualm.es
Fax: +34-50-215465

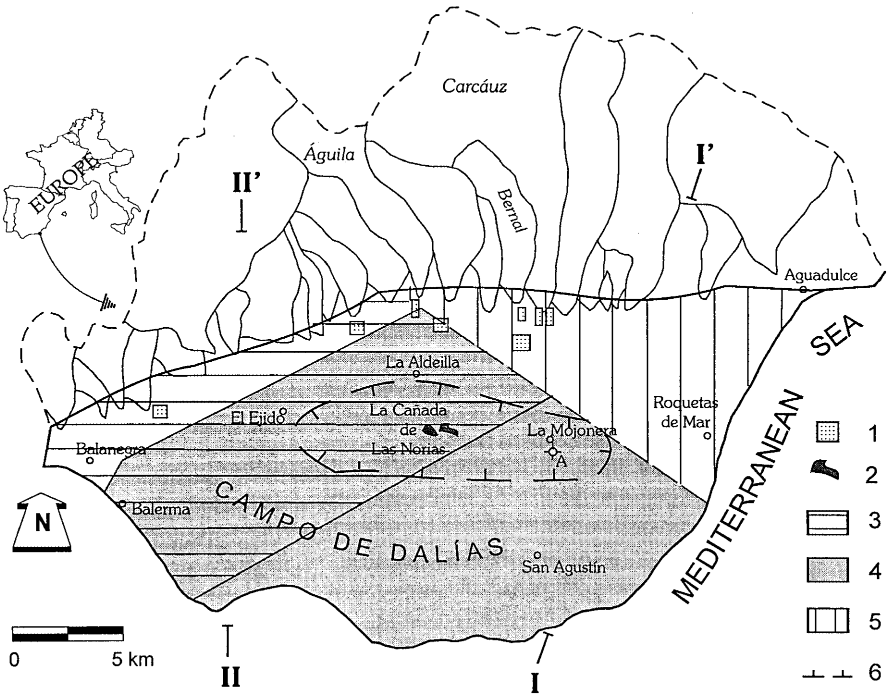

Fig. 1
Hydrological scheme of the Campo de Dalias and its geographical situation. *1* Location of the principal gravel pits; *2* lutites pits. *3* Balanegra unit; *4* Balerma-Las Marinas unit; *5* Aguadulce unit; *6* endoreic area

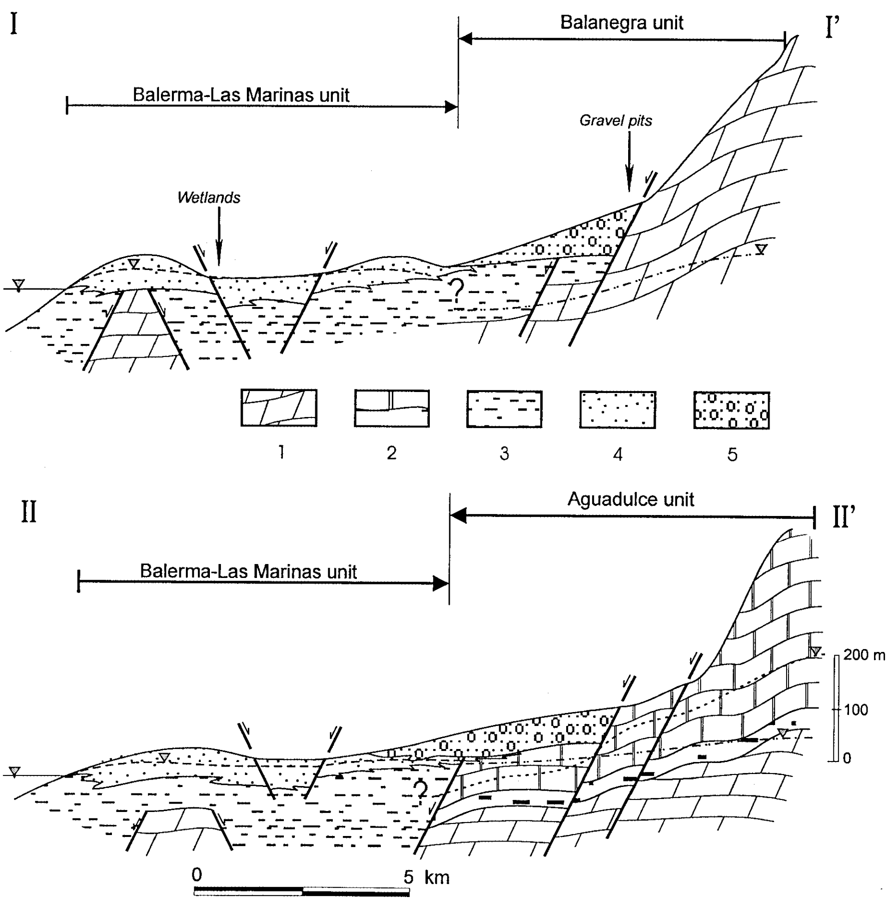

Fig. 2
Two schematic cross sections of the Campo de Dalias system. Their location is shown in Fig. 1. *1* Carbonates from the Gador unit; *2* carbonates and phyllites from the Felix unit; *3* Pliocene marls; *4* Pliocene calcarenites; *5* Quaternary alluvial fans

most important hydrogeological units that are differentiated (Figs. 2 and 3): Balerma-Las Marinas, essentially composed of Pliocene calcarenites; Balanegra, which occupies the western half and basically consists of Gador carbonates; and the Aguadulce unit, situated in the eastern half and consists of the rocks of the units of Gador and Felix in an extremely complex geometric disposition (Rodríguez and Martin 1993).

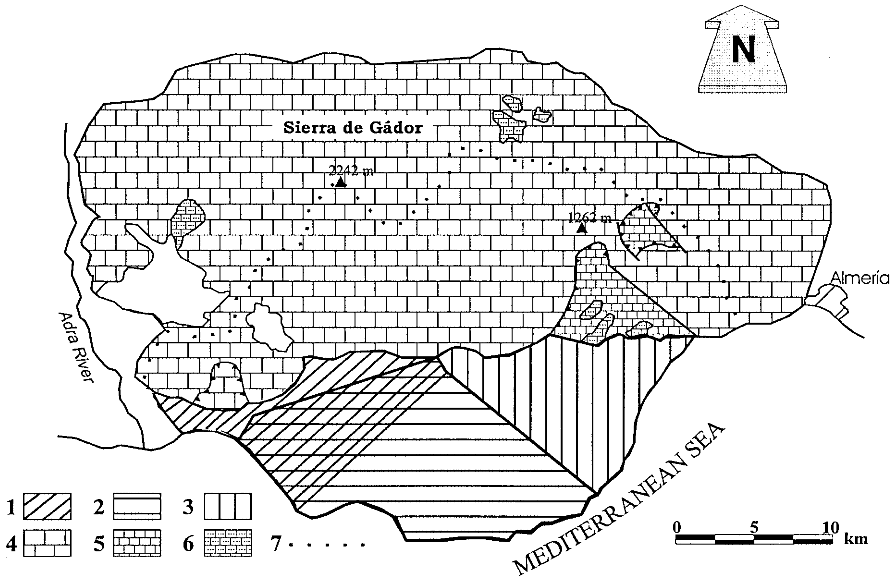

Fig. 3
Hydrogeological scheme of the Sierra de Gador-Campo de Dalias. *1* Balanegra unit; *2* Balerma-Las Marinas unit; *3* Aguadulce unit; *4* Gador unit; *5* Felix unit; *6* Miocene calcarenites; *7* watershed

The Balerma-Las Marinas unit covers $\sim 225\ km^2$ and is mainly comprised of Pliocene calcarenites and detrital Quaternary sediments. Their thickness reaches 120 m, decreasing from north to south. Transmissivity values vary from 120 to 1200 m^2/day based on various pumping tests (Pulido-Bosch and others 1991).

The Balanegra unit occupies the western side and covers nearly 200 km^2. It is comprised mainly of dolomites and limestones of the Gador unit. A large part of this unit is covered by the Balerma-Las Marinas unit, though separated by the Pliocene marls. Transmissivity values can reach 15,000–22,000 m^2/day.

The Aguadulce unit has a very complex geometry (Figs. 2 and 3). It is possible to find several aquifer formations superimposed, including carbonates from the Gador and Felix units, Miocene and Pliocene calcarenites and Quaternary detrital sediments, separated by metapelitic formations and Pliocene marls. Transmissivity values can reach more than 10,000 m^2/day with high porosity (Vallejos and others 1997).

Of these three units, the first is only exploited by drilling wells to a small degree, largely on account of the elevated saline content (natural or partly induced) of its waters (Pulido-Bosch and others 1990, 1991). In contrast, the other two units have been the focus of intensive exploitation over the last 30 years (Pulido-Bosch 1989, 1991; Dominguez and Gonzalez 1995) and this exploitation has given rise to processes of marine intrusion associated with drawdown cones that can exceed 20 m below sea level. The overall decline in water levels in numerous drilling wells that pump from these units has exceeded 60 m.

Given this context, the prime objective of this article is to highlight a curious example of agricultural development that has had a series of environmental impacts. Large pits have been opened for the extraction of significant quantities of clays and gravels for agricultural purposes, two of the three hydrogeological units have become overexploited and, at the same time, several wetlands have appeared as a consequence of irrigation practices. At the same time, we wish to demonstrate that the gravel pits could be used as large artificial recharge basins, complemented by a series of small dams and infiltration ditches, with the aim of better managing the water resources of this semi-arid area, which suffers a great water deficit.

Origin of the quarries

Intensive agriculture began in the Campo de Dalias at the end of the 1940s (Navarrete 1992), although it was not until the 1970s that it acquired greater economic significance. The cultivation system is highly unusual in that it does not require favourable edaphic conditions. Effectively, it consists of the following: after levelling the ground as well as possible, a silty-clay substratum is laid. A layer of animal manure or compost is laid over the top, which is then covered by a layer of gravel. Thus, in addition to manure, the raw materials include lutitic materials and gravels (Fig. 4).

The lutitic materials are derived, for the most part, from a series of pits excavated in the distal parts of the alluvial fans, as described earlier. These are highly-developed in the vicinity of the area of maximum endoreism (Las Norias, La Mojonera, La Aldeilla, San Agustín), called La Cañada de Las Norias (Castro and others 1999; see Fig. 7). It is estimated that the quarries cover a surface area of >150 ha. The volume of material extracted, basically lutites, is in the order of $8\times10^6\ m^3$, and this gives some idea of their importance.

The gravels initially came from the beach areas, but the prohibition of extractive activities by the competent authority dictated that new extraction points be found, especially in the apical parts of the alluvial fans. There are pits at other points within these fans, notably the large

Fig. 4
Preparation of the ground for greenhouse cultivation

Fig. 5
View of the gravel pit between the ramblas of Bernal and Vícar. The machine in the distance gives an idea of scale

gravel pit (Fig. 5) that lies between the ramblas of Bernal and Carcauz (Fig. 1), which has a capacity of close to 1×10^6 m^3 and a depth of >30 m. Altogether, more than 5×10^6 m^3 of these materials have been extracted. Figure 1 shows the principal sectors of extraction. As a consequence, a very unevenly developed series of pits has arisen, which confers a significant impact on the landscape.

The extraction pits and hydrogeological functioning

One of the most unusual aspects related to extractive activity is concerned with the hydrogeological implications that the pits for lutitic materials have since been abandoned. In effect, the greater part of these pits is situated over the Balerma-Las Marinas unit, which is comprised basically of Pliocene calcarenites. The waters of this unit have traditionally been little exploited because they usually exhibit high salinity. However, a significant proportion of agriculture is realised over these formations, and the reason for the continuous rise in the water table in this unit (Fig. 6) is because of the return-flow of irrigation water. The elevated nitrate content of the waters within this unit corroborates this process (Pulido-Bosch and others 1999). This is in contrast to what happens in the other two units (Dominguez and Gonzalez 1995), where the level is situated below seawater level over wide areas, and the waters have low concentrations of nitrates. The rise in the phreatic level of the Balerma-Las Marinas unit has been such that, over the last few rainy years, the bases of the pits have begun to flood. Currently, they cover a surface area of close to 150 ha, with up to 2 m depth of water in places. The Junta de Andalucia Government, aware of the ecological interest of these wetlands because of the array and quantity of animals that have installed themselves there, examined the possibility of declaring them protected areas, despite their singular location and curious origin. Unfortunately, farmers find these pits very suitable repositories for wastes generated by agricultural activities. Many are filled to the brim with inert wastes, whereas others are full of degradable materials. This means that a certain amount of pesticide containers may be present at the bottom of the pools, as well as every sort of agricultural debris and/or greenhouse rubbish (plastic, cables, construction materials etc.). Additionally, in one of the pits, a secure tip has been installed into which substances that are more toxic than domestic waste or conventional agricultural waste are tipped, although a series of special precautions were taken when the tip was constructed.

The gravel pits

Because of the high energy developed by the periodic storm waters in the ramblas that drain the southern margin of the Sierra de Gador, the granulometry of the transported sediment is extremely heterogeneous, ranging from boulders of several cubic metres volume, to lutite-sized particles, although, in keeping with the fact that we are dealing with an area away from the apical zone, the granulometry is more homogeneous (Fig. 8).
In contrast, cemented and encrusted sections exist, which impede their use as materials for the greenhouses. As a consequence, extraction spoil can be found in these pits that can include large blocks and fragments of encrusted strata. It is necessary to specify that the hydrological functioning of these ramblas is essentially determined by the intensity and quantity of precipitation, by the slope, and by the permeability and lithology of the formations that constitute the catchment.
As was indicated earlier, a considerable part of the Campo de Dalias lacks a direct outlet to the sea so that, in the event of floods, all of the endoreic sector could be left under water, including the wetland zone. Here, the water

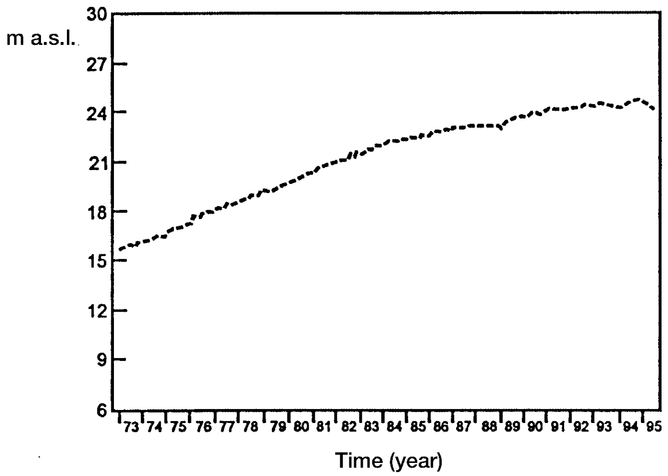

Fig. 6
Evolution of the water level in a borehole located in the Balerma-Las Marinas Unit (modified from Dominguez and Gonzalez 1995)

Fig. 7
Panorama of the western sector of the wetland of Cañada de las Norias

depth in an extreme flood could reach a maximum depth of 18 m (Gutierrez 1996) before being able to start draining towards the sea.

As a complement to the above, we can specify that 107 check dams exist along the length of the southern edge of the Sierra de Gador, of variable size and characteristics, and have been constructed by the central and regional administrations since 1977 (Martin-Rosales 1997). These dams fulfil three potential purposes: to reduce erosion, to smooth flood flows, and to facilitate aquifer recharge where the streambed lies over permeable materials.

On the other hand, the intensive exploitation to which the Campo de Dalias has been subjected has had diverse consequences that can be summarised as follows: a continued decline in the piezometric levels, which, in some areas, are situated at >20 m below sea level; the appearance of marine intrusion processes, especially evident in

Fig. 8
View of one of the gravel pits situated in the Carcauz rambla

the Aguadulce Unit; and mobilization of waters of elevated saline content that are retained within the sediments (Molina 1998). Bearing in mind the intensive exploitation and the risks of floods, it seems appropriate to utilise some of the existing gravel pits on the alluvial fans for artificial recharge, contributing at the same time to reduce the risk of catastrophic floods. This option is relatively in-keeping with the environment: its impact is minimal, it could be highly efficient and its cost would be low.

Consequently, on 7 March 1991, we took the opportunity to record a storm. During this storm, the elevated infiltration potential of the gravel pits in the Aguila rambla was highlighted. A total of 85 mm of rain fell over 10 h, giving rise to a flood with a peak flow estimated at 3 m^3/s. The floodwater eroded a gabion dam (Fig. 9), although all the water infiltrated into gravel pits downstream (Fig. 8).

Clearly, the use of the gravel pits for artificial recharge would bring not only advantages: it would carry with it the need for continuous maintenance, especially as each flood would deposit a muddy layer, and the infiltration rate might be progressively reduced. This potential use of the gravel pits could be complemented by establishing a network of strategically placed infiltration ditches over the length and breadth of the alluvial fans (Pulido-Bosch and others 1998). We have undertaken 13 infiltration tests in the beds of various ramblas using the Muntz or double ring method. The values obtained (presented as instantaneous infiltration capacity) fell within the range of 2–>1000 mm/h, with a mean value of 165 mm/h.

Final considerations

The Campo de Dalias constitutes a singular example of the possible application of abandoned gravel pits for artificial recharge. It would take advantage of their position at the head of the alluvial fans that punctuate the Sierra de Gador. Artificial recharge to the gravel pits could be a

Fig. 9
Gabion dam eroded by the flood of 7 March 1991

useful tool in the management of water resources in the area, and it could contribute towards mitigating the marked water deficit that exists in the area as a consequence of the overexploitation of the aquifers. In addition, it will permit a significant reduction in the risk of catastrophic floods caused by the high-intensity rainfall events, which have a return period of around 50 years (Martin-Rosales and others 1996).

Another unusual feature of this area is the appearance of wetlands related to the extraction of essentially clayey materials, exploited in the endoreic sector of the Campo for use as a substratum for greenhouse crops.

The particularly problematical hydrology and hydrogeology in this region (risk of catastrophic floods and the overexploitation of the aquifers) allow us to conclude that both results of the extraction activities, which are apparently so degradative, could turn out to provide a significant positive environmental role. Specification of the works required (adaptation of the quarry pits, and complementary dams and ditches from which the artificial recharge would occur) needs to be the subject of a detailed study that would take into account the hydrodynamic and hydrogeological geometry, as well as hydrometeorology (quantity and intensity of rainfall, in particular). The 107 dams that exist along the southern edge of the Sierra de Gador guarantee an infiltration of 10% of the maximum precipitation for a 10-year return period, and the lamination of the peak flow of up to 21% (Martin-Rosales 1997). To these values have to be added the high infiltration capacity of the gravel pits, which, in the flood observed in March 1991, allowed a total infiltration of the surface run-off. In addition, there would be the contribution of suitably designed, complementary, infiltration ditches.

Acknowledgements This paper has been partially prepared in the framework of the Project HID98-0689, financed for the Spanish Comisión Interministerial de Ciencia y Tecnología (CICYT).

References

Aguirre J (1999) El Plioceno del SE de la Península Ibérica (provincia de Almería). Síntesis estratigráfica, sedimentaria, bioestratigráfica y paleogeográfica. Rev Soc Geol España 11 (3–4):297–315

Castro H, Carrique EL, Aguilera PA, Ortega M, Casas JJ, Rescia A, Schmitz MF, Pineda FD (1999) Humedales almerienses: importancia, problemática y gestión. In: Pulido-Bosch A, Calaforra JM, Pulido-Leboeuf P Jornadas sobre el Agua, pp 31–46

Dominguez P, Gonzalez A (1995) Situación de los acuíferos del Campo de Dalias (Almería) en relación con su declaración de sobreexplotación. Hidrogeol Recur Hidrául XXI:443–467

Gutierrez MA (1996) El agua en el Poniente Almeriense. IV SIAGA. Almería III:141–155

Martin-Rosales W (1997) Efectos de los diques de retención en el borde meridional de la Sierra de Gador (Almería). PhD Thesis, University Granada

Martin-Rosales W, Pulido-Bosch A, Vallejos A, Lopez-Chicano M (1996) Precipitaciones máximas en el Campo de Dalias y vertiente meridional de la Sierra de Gador (Almería). Geogaceta 20(6):1251–1254

Molina L (1998) Hidroquímica e intrusión marina en el Campo de Dalias (Almería). PhD Thesis, University of Granada

Navarrete F (1992) Contribución al conocimiento hidrogeoquímico del Campo de Dalias (Andalucia). PhD Thesis, University of Granada

Pulido-Bosch A, Martinez-Vidal JL, Navarrete F Benavente J, Molina L, Gonzalez V, Macías A, Padilla A (1989) Caracterización hidrogeoquímica del Campo de Dalias (Almería). IARA – Junta de Andalucia, Sevilla

Pulido-Bosch A, Navarrete F, Molina L, Martinez-Vidal JL (1990) Principales características hidrogeoquímicas del acuífero de Balerma-Las Marinas (Almería). Estud Geol 46(3–4):291–300

Pulido-Bosch A, Navarrete F, Molina L, Martinez-Vidal JL (1991) Quantity and quality of ground-water in the Campo de Dalias (Almeria, Spain). Water Sci Technol 24:87–96

Pulido-Bosch A, Martin-Rosales W, Vallejos A, Molina L, Calaforra JM (1998) Los diques como elemento en la gestión de los recursos hídricos de la provincia de Almería. Simposio de Minería, Industria y Medio Ambiente en la Cuenca Mediterránea. Abstracts, Univ Almería, p 64

Pulido-Bosch A, Bensi S, Molina L, Vallejos A, Calaforra JM, Pulido-Leboeuf P (1999) Nitrates as indicators of aquifer interconnection. Application to the Campo de Dalias (SE-Spain). Environ Geol (in press)

Rodríguez J, Martin A (1993) Neogene evolution of the Campo de Dalias and the surrounding offshore areas (northern Alboran Sea). Geodinamica Acta 6–4:255–270

Vallejos A, Pulido-Bosch A, Martin-Rosales W, Calvache ML (1997) Contribution of environmental isotopes to the understanding of complex hydrogeologic systems. A case study: sierra de Gador, SE Spain. Earth Surf Process Landforms 22:1157–1168