ELSEVIER

Journal of Hydrology 265 (2002) 43–55

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Using stable isotope analysis ($\delta D-\delta^{18}O$) to characterise the regional hydrology of the Sierra de Gador, south east Spain

G. Vandenschrick[a,*], B. van Wesemael[a*], E. Frot[a], A. Pulido-Bosch[b], L. Molina[b], M. Stiévenard[c], R. Souchez[d]

[a]*Département de Géographie, Université Catholique de Louvain, 1348 Louvain-la-Neuve, Belgium*
[b]*Department of Hydrogeology, University of Almeria E04120-La Cañada, Almeria, Spain*
[c]*Laboratoire des Sciences du Climat et de l'Environnement, CEA Saclay, F-91191 Gif/Yvette, France*
[d]*Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, CP160/03, B1050 Brussels, Belgium*

Received 24 April 2001; revised 15 February 2002; accepted 19 April 2002

Abstract

Water stress is rapidly increasing in many Mediterranean coastal zones mainly due to expansion in agriculture and tourism. In this paper, we focus on the Sierra de Gador–Campo de Dalias aquifer system (southeastern Spain) in order to assess the capability of water stable isotope analysis ($\delta D-\delta^{18}O$) to refine the understanding on recharge of this karstic aquifer system. Different types of surface and groundwater were sampled along an altitudinal gradient from the recharge zone in the mountains to the coastal plain. Surface water is restricted to local runoff, collected in closed reservoirs. Runoff amounts, collected in three of these reservoirs were monitored together with the precipitation in their catchments. Meteorological maps were used to detect the origin of the precipitation generating the majority of the runoff. The results were compared to literature data on local and regional precipitation. The use of oxygen and hydrogen isotopic composition has proved to be a useful tool to explain the origin of groundwater in a Mediterranean karstic system. Such studies are, however, not numerous and are often limited to local scale recharge for fast-reacting systems. This paper focuses on the $\delta^{18}O-\delta D$ relationships of local precipitation to explain the isotopic variability of a large karstic aquifer system. The isotopic compositions of groundwater sampled along an altitudinal gradient from the recharge zone to the coastal plain are well displayed, in a $\delta D-\delta^{18}O$ diagram, on a mixing line connecting a pole of Mediterranean waters to a pole of Atlantic waters. The Atlantic signature predominates in the shallow groundwater of natural springs, reflecting the rainfall which produced the local runoff sampled. The Mediterranean signature is mainly restricted to deep groundwater from boreholes in the coastal plain. The existence of a degree of spatial separation of groundwater types demonstrates that groundwater flow in a complex karstic system is not always continuous. The Mediterranean signature of deep groundwater could be due to past extreme rainfall events during which connectivity between recharge and reservoir exists, while at the same time the Atlantic signature of recent winter rains dominates in shallow groundwater. The assumption that an equilibrium in isotopic composition is established within a continuous aquifer and that therefore a slope lower than 8 in a $\delta D-\delta^{18}O$ diagram indicates evaporation is not necessarily valid. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Water stable isotopes; Groundwater recharge; Precipitation origin; Karst; Spain

---

* Corresponding authors. Tel.: +32-10-472056; fax: +32-10-472877.
E-mail address: vanwesemael@geog.ucl.ac.be (B. van Wesemael).

PII: S0022-1694(02)00097-5

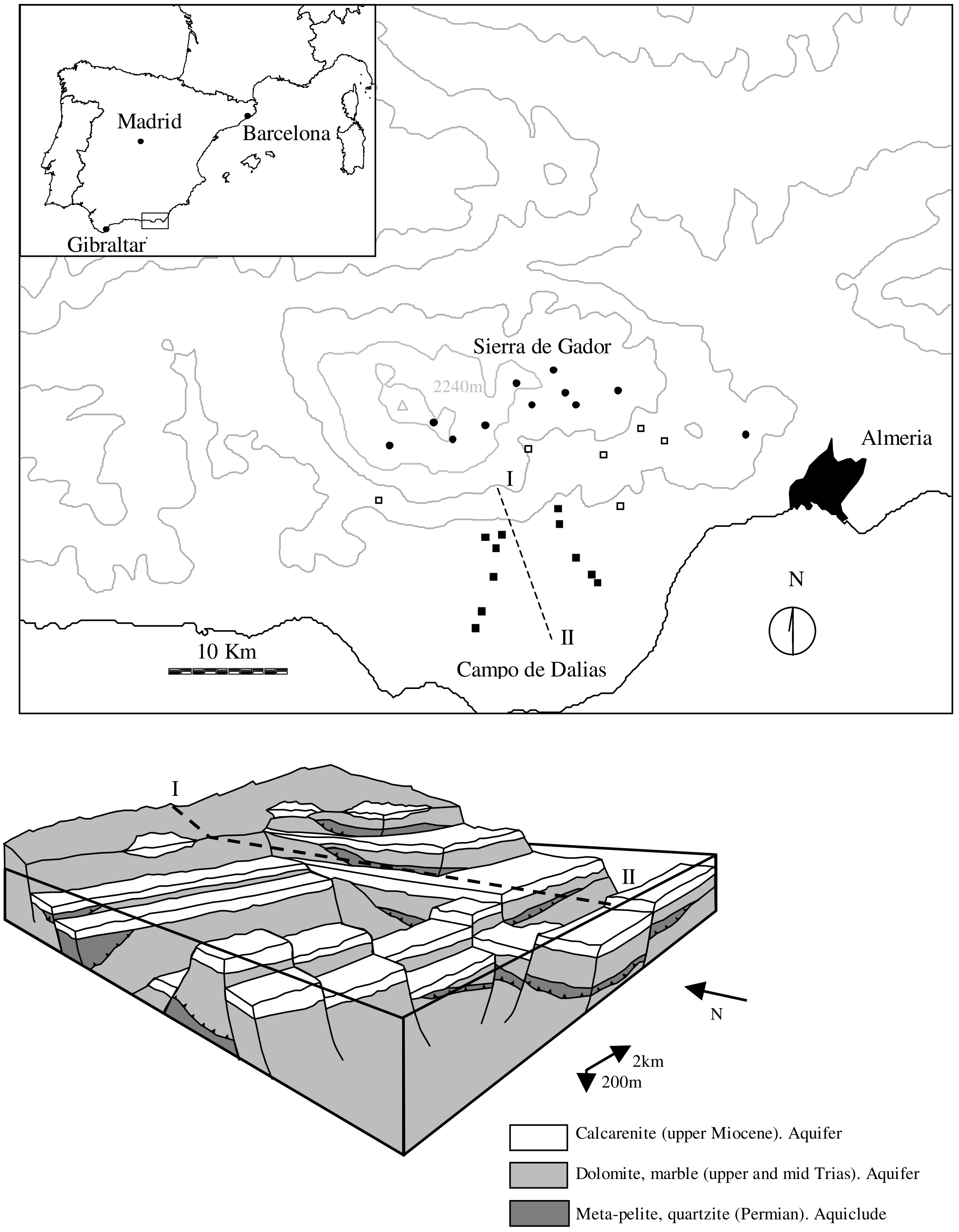

Fig. 1. Location of the sampling sites: boreholes (black squares), springs (open squares) and local runoff (black circles). Geology of the Campo de Dalias and Sierra de Gador piedmont; redrawn from Pulido-Bosch et al. (1993). Note that the Quaternary and Pliocene sediments have been removed in the schematic representation.

1. Introduction

The combined study of oxygen and hydrogen isotopes in water is a promising tool for exploring hydrological fluxes at a regional scale. The interest for the hydrological framework of the Sierra de Gador and Campo de Dalias (southeastern Spain; Fig. 1) can be explained by the intensive exploitation of this aquifer for irrigation of early season horticulture and a growing water demand from tourism (Tout, 1990; Pulido-Bosch et al., 1993; Vallejos et al., 1997). Vallejos et al. (1997) focused on the analysis of stable isotopes from boreholes on the fringe between the Sierra de Gador and the coastal plain. They indicated that precipitation of Mediterranean origin infiltrating on the slopes of the Sierra de Gador is probably the main source for recharge of the aquifer. This can be questioned, since only a single rain event was used to characterise the isotopic signature of the precipitation in an area which is known for the occurrence of precipitation of both Mediterranean and Atlantic influences. Lazaro et al. (2001) reiterate the strong seasonal differences in precipitation origin for the coastal area of south east Spain. Rain bearing fronts from the Atlantic Ocean during the winter months are determined by the December North Atlantic Oscillation. After summer and during autumn, fronts coming from the Mediterranean dominate, resulting sometimes in torrential rainfall. These Mediterranean fronts are controlled by the October Southern Oscillation. Isotopic studies in the western Mediterranean are rare, and therefore the relative proportion of Atlantic versus Mediterranean rainfall is only known in very few sites. Celle-Jeanton et al. (2001) state that Western Mediterranean precipitation is typically aligned in a $\delta D - \delta^{18}O$ diagram on a local meteoric water line with a deuterium excess of c. $+15‰$, indicating the unique isotopic characteristics of the Western Mediterranean between the Atlantic and Eastern Mediterranean regions.

The distinct isotopic signature of precipitation with a Mediterranean origin has been used in hydrological studies in the eastern Mediterranean region (Kattan, 1997; Ayalon et al., 1998). However, these studies do not address the spatial variation in isotopic signature of large aquifer systems, for which source and age interpretations are known to be difficult (Davisson et al., 1999). We concentrate here on the distinction between Atlantic and western Mediterranean origin of precipitation and its impact on the isotopic signature of surface and groundwater along its pathway from the summits of the Sierra de Gador towards the deep limestone aquifers in the coastal plain. The abundance of traditional water harvesting reservoirs at a range of altitudes in the mountains and boreholes along transects through the coastal plain gives access to water at different stages along its pathway through the aquifer system: local runoff water collected from impermeable surfaces and stored in closed reservoirs (Spanish: aljibes), shallow groundwater from springs, and deep groundwater pumped from the coastal plain aquifers. The aim of this paper is to investigate whether the $\delta D - \delta^{18}O$ relationships commonly used to explain local scale recharge remain valid when considering the recharge of a complex karstic aquifer in the western Mediterranean.

2. Study area

The Sierra de Gador is located in southeastern Spain just west from the town of Almeria (Fig. 1). It is a mountain range reaching 2242 m asl and consisting of a thick series of Triassic carbonate rocks, i.e. highly permeable, fractured rocks with intercalated calcschists of low permeability underlain by impermeable metapelites of Permian age. A system of faults delimits the footslopes of the Sierra de Gador on the fringe of the coastal plain (Campo de Dalias, Fig. 1). In the Campo de Dalias, the carbonate rocks forming the outcrops in the Sierra de Gador are buried under Miocene and Pliocene sediments that can reach a thickness of up to 500 m. These Miocene and Pliocene sediments contain important aquifers such as the calcarenites. Vallejos et al. (1997) state that the carbonate rocks in the Campo de Dalias are hydrologically connected to the ones in outcrops in the Sierra de Gador and that the carbonate aquifers became disconnected from the Pliocene calcarenites with the increased exploitation of the groundwater system as the piezometric level fell. As a result of large-scale deforestation during the 18th and 19th century in the Sierra de Gador, vegetation is generally sparse and soils are very thin and rocky. Therefore, the southern side of the Sierra de Gador where the

Table 1
Results of the isotopic analysis of local runoff and groundwater

Altitude (m)	Date	δD (‰ ± 0.5‰)	δ^{18}O (‰ ± 0.05‰)	d (‰)
Closed runoff reservoirs				
1550	28/10/1999	−70.9	−9.9	8.3
1180	28/10/1999	−67.5	−9.5	8.5
1690	28/10/1999	−63.2	−9.5	12.8
1840	28/10/1999	−59.6	−9.3	14.8
1416	27/10/1999	−64.9	−9.2	8.7
1361	31/10/1999	−58.2	−8.8	12.2
1419	27/10/1999	−56.5	−8.5	11.5
1340	27/10/1999	−57.5	−8.3	8.9
1990	28/10/1999	−52.9	−7.9	10.3
1990	23/01/2001	−50.8	−7.6	10
1419	26/01/2001	−66	−9.5	10
1416	26/01/2001	−64.7	−9.1	8.1
1340	26/01/2001	−57.8	−8.4	9.4
550	28/01/2001	−43.7	−6.8	10.7
1180	28/01/2001	−66.8	−9.4	8.4
1550	28/01/2001	−70.1	−9.8	8.3
1690	28/01/2001	−63.8	−9.6	13
Deep groundwater: boreholes				
79	30/10/1999	−61.7	−9.6	15.1
80	30/10/1999	−61.7	−9.5	14.3
270	30/10/1999	−59.8	−9.3	14.6
100	30/10/1999	−57.5	−9	14.5
70	30/10/1999	−57.1	−8.9	14.1
100	30/10/1999	−56.2	−8.8	14.2
343	30/10/1999	−55.8	−8.6	13
250	30/10/1999	−52.9	−8.4	14.3
200	30/10/1999	−52.8	−8.3	13.6
200	30/10/1999	−53	−8.2	12.6
130	30/10/1999	−45.4	−7.1	11.4
Shallow groundwater: springs				
970	28/10/1999	−47.9	−7.6	12.9
580	29/10/1999	−60.8	−9.5	15.2
770	29/10/1999	−53.9	−8.4	13.3
812	29/10/1999	−48.5	−7.5	11.5
720	28/10/1999	−46.4	−7.2	11.2
400	29/10/1999	−44.4	−7.1	12.4
812	28/01/2001	−48.4	−7.5	11.6
720	28/01/2001	−45.9	−7.1	10.9
970	28/01/2001	−42.6	−6.7	11
400	28/01/2001	−44.7	−7.2	12.9
580	28/01/2001	−60.6	−9.4	14.6

present study was undertaken is vulnerable to flash floods (Pulido-Bosch et al., 1993, 2000). The study area has a semi-arid climate with strong altitudinal gradients in annual precipitation (P) and temperature (T): $P = 171$ mm and $T = 17.9$ °C on the southern footslopes; $P = 600-650$ mm and $T = 11-12$ °C on the summits (Lazaro and Rey, 1991). Since the 1960s, irrigated horticulture which produces early season crops for European consumers (Tout, 1990), has become the main land use in the Campo de Dalias. Traditional small-scale agriculture and pasture prevail in the Sierra de Gador and depend mainly on springs and storage of local runoff in closed reservoirs locally known as aljibes (Cara and Rodriguez, 1989; van Wesemael et al., 1998). Pulido-Bosch et al. (1993, 2000) have highlighted the water stress in the Campo de Dalias (360 km^2) with an estimated number of boreholes at around 1200, an annual water use of 130 hm^3 in 1998 and an estimated annual recharge of 48–54 hm^3.

3. Methods

Water samples were collected for a co-isotopic study in the Sierra de Gador, on its lower southern slopes and in the coastal plain of the Campo de Dalias (Fig. 1, Table 1). Eleven closed runoff reservoirs along an altitudinal gradient from 550 to 1990 m asl and six springs on the contact between the carbonate rocks and the metapelites between 400 and 970 m asl were sampled in October 1999 and January 2001. Furthermore, 11 samples were collected from irrigation boreholes, in October 1999. The latter are all located between 70 and 343 m asl in the Campo de Dalias and in the Sierra piedmont. These boreholes reach into the Triassic carbonate aquifer at depths ranging from 200 m at the Sierra piedmont to 900 m in the central zone of the Campo de Dalias. From the continuous monitoring of the water level in three closed runoff reservoirs and pluviograph records, we were able to identify the rain events which had contributed significantly to the runoff sampled. The meteorological conditions during these events were reconstructed from weather maps provided by Météo-France.

All samples were stored in small glass bottles with watertight caps. In order to avoid any evaporation, the bottle, just after sampling, was wrapped into a parafilm which was fixed. As soon as this was done, the bottles were transferred in a dark container to avoid direct sunlight. No chemicals were added to the water. The isotopic measurements were carried out at

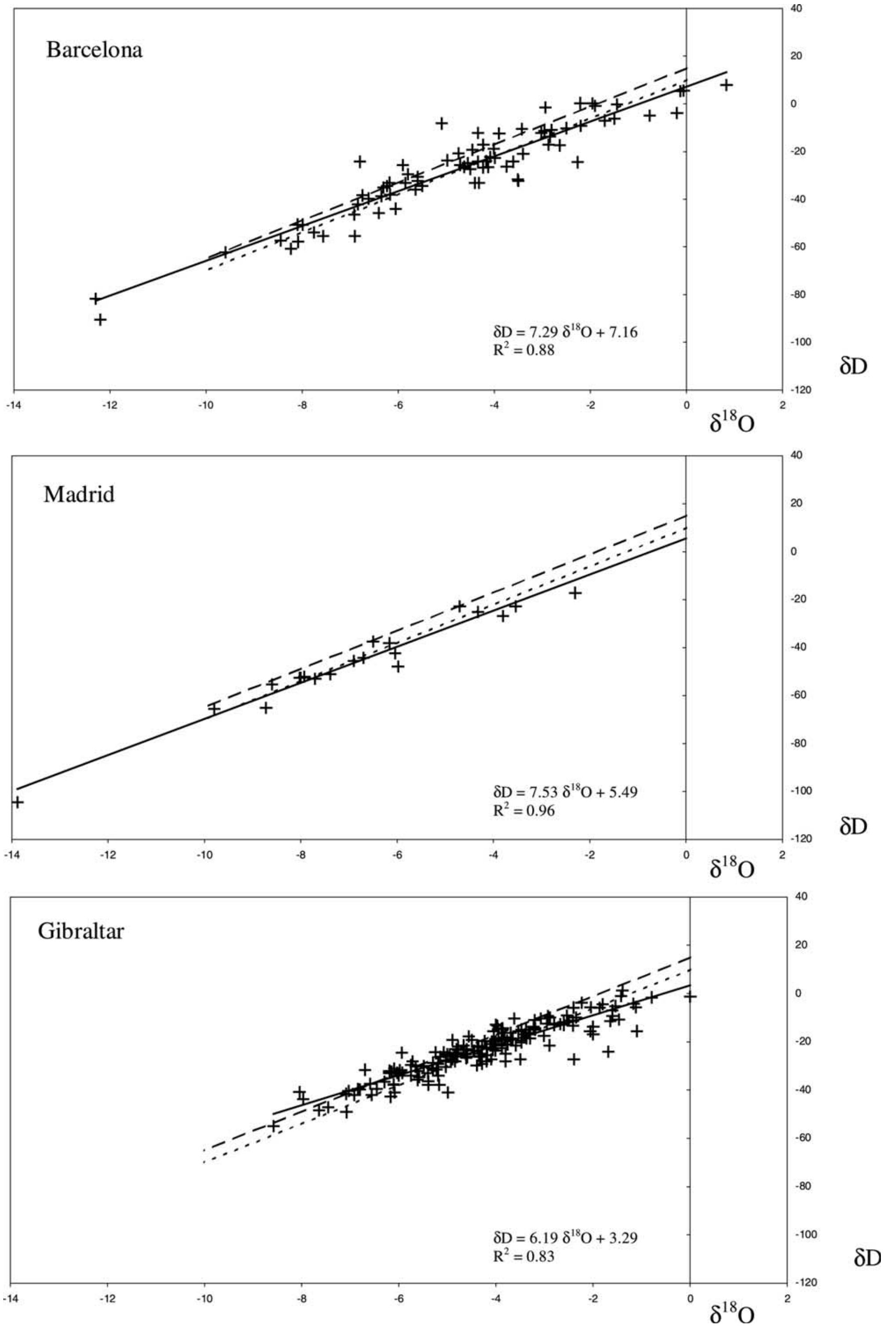

Fig. 2. $\delta D-\delta^{18}O$ relationship from Barcelona, Madrid and Gibraltar precipitation samples (GNIP data; IAEA/WMO, 2001) with regression lines (solid). The global meteoric water line (GMWL) (dotted line) and the western Mediterranean Meteoric Water Line (WMMWL) (dashed line) are also indicated.

the Centre d'Etudes Nucléaires de Saclay in France. The concentrations are given hereafter in δ-units calculated with respect to VSMOW (Vienna Standard Mean Ocean Water) expressed in part permil (Eq. (1))

$$\delta_{\text{sample}}\ (\text{‰}) = 1000\left[\frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}}\right] \tag{1}$$

where R_{sample} and R_{VSMOW} are the isotopic ratios of the sample and of the VSMOW, respectively. The accuracy of the measurements is ±0.5‰ in δD and ±0.05‰ in δ^{18}O. Thanks to this accuracy, not only precise δD–δ^{18}O relationships can be derived from the data, but also small differences in deuterium excess ($d = \delta\text{D} - 8\delta^{18}\text{O}$) can be considered since this parameter exhibits less variability.

4. Results and discussion

4.1. Isotopic composition of regional precipitation

Interpretation of the isotopic signature of the different water types in the Sierra de Gador is facilitated by a discussion of the regional precipitation. This data is available on the Internet in the framework of the global network of isotopes in precipitation (IAEA/WMO, 2001). The δ-values for precipitation are available for Barcelona from January 1984 to December 1991, for Madrid from January 1988 to December 1989, and for Gibraltar from January 1962 to December 1995. The δD and δ^{18}O values are given in the form of mean monthly values (Fig. 2). We use these GNIP data for the three Spanish stations in order to derive δD–δ^{18}O relationships and to understand the isotopic characteristics of the precipitation. The straight lines in the δD–δ^{18}O diagram obtained by linear regression for Barcelona and Madrid have a slope close to 8 (7.29 and 7.53, respectively, with $R^2 = 0.88$ and 0.96) and can be considered as local meteoric water lines (LMWL). However, the straight line obtained for Gibraltar has a slope lower than 8 (6.19 with $R^2 = 0.83$).

The major sources of water vapour at the origin of precipitation in Spain are the Mediterranean basin and the Atlantic ocean. Isotopic characteristics like δ-values and deuterium excess values, can be considered as discriminating tools for such origins. The δ-values, either δD or δ^{18}O values are more negative if the source of the water vapour at the origin of the precipitation is further away (distance effect), if a large part of the water vapour is precipitated from the cloud (reservoir effect) or if the temperature is lower. This can be ascribed to impoverishment in heavy isotopes during successive precipitations, to depletion of the water vapour from the cloud or to a higher value of the equilibrium fractionation coefficients for oxygen 18 and deuterium with lower temperature. Deuterium excess is the independent term of the equation $\delta\text{D} = 8\delta^{18}\text{O} + d$ corresponding to what is referred to as the Meteoric Water Line. If evaporation rates are high, because of high temperature and low relative humidity in the atmosphere during the formation of the water vapour, there is a strong kinetic isotopic effect, and d becomes higher (Jouzel and Merlivat, 1984). Deuterium excess is usually considered as a more or less conservative property in the part of the atmospheric water cycle beginning with water vapour formation by evaporation to rainfall just below cloud level (Ciais and Jouzel, 1994). Deuterium excess in rainfall of Mediterranean origin generally has a relatively high value. This is due to a strong kinetic isotopic effect during evaporation in the summer above the Mediterranean Sea because of the low relative humidity of the atmosphere. Conversely, Atlantic precipitation has a deuterium excess around +10‰.

If the rain results from a mixing between water vapours of Mediterranean and Atlantic origins, it will be represented, in a δD–δ^{18}O diagram, on a straight line called a mixing line. This line will connect a pole of Atlantic points characterised by d-values around +10‰, to a Mediterranean pole with higher d-values. Slopes close to 8 are displayed for Barcelona and Madrid (Fig. 2), indicating a common origin for all events or at least similar kinetic conditions at the water vapour source (relative air humidity and temperature). By contrast, the slope inferior to 8 for Gibraltar could be the signature of evaporation during precipitation travel from the cloud to the ground surface (Gonfiantini, 1986). This evaporation would be responsible for enrichment in heavy isotopes of the residual liquid water and for a decrease in

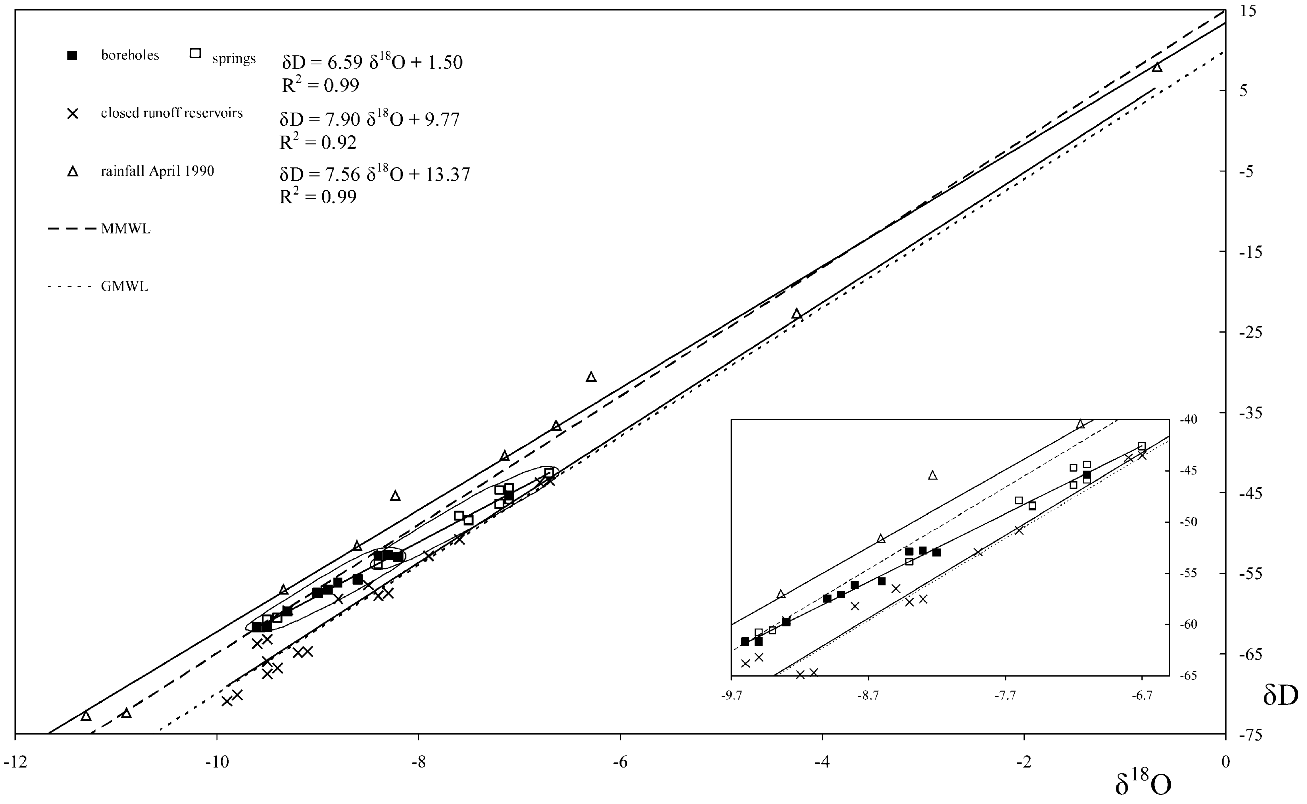

Fig. 3. δD–δ^{18}O relationships for the different water types: April 1990 rains, local runoff, springs and boreholes with their regression lines.

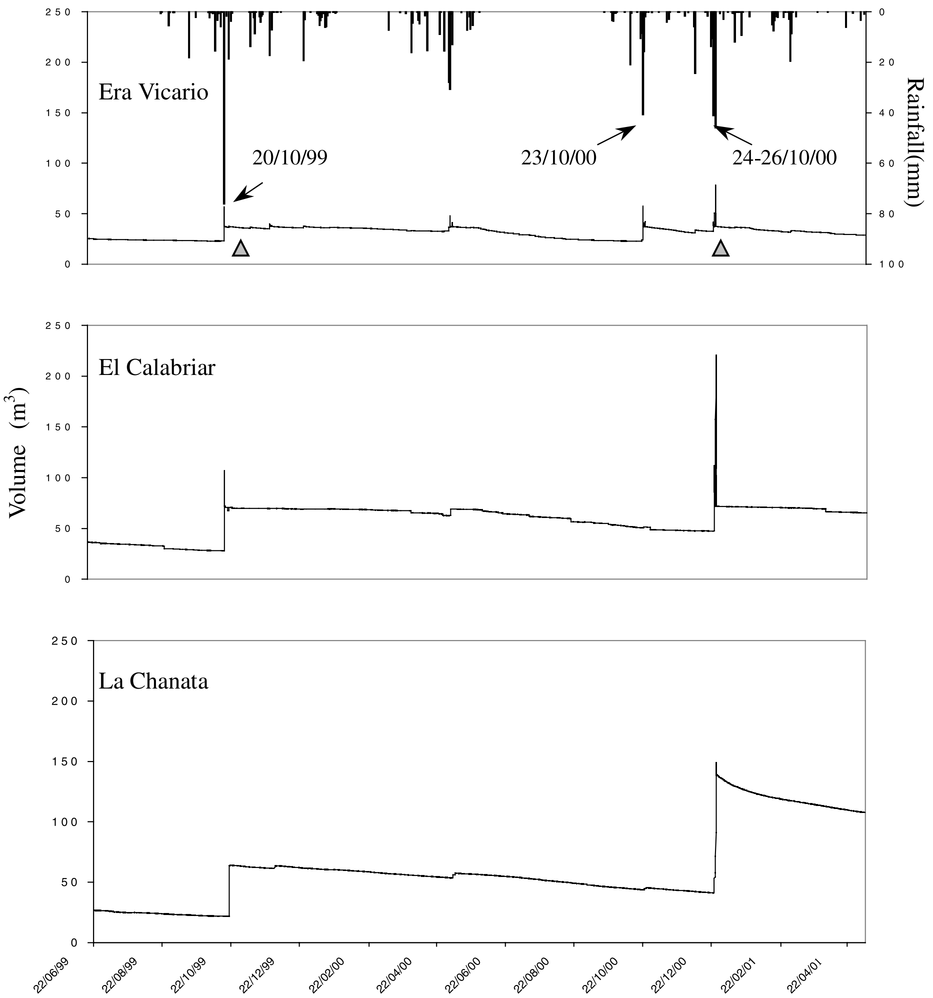

Fig. 4. Water quantities (m^3) in three closed runoff reservoirs (El Calabriar, La Chanata, Era Vicario) from June 1999 to April 2001 and rainfall quantities (mm/day). Sampling dates are marked by triangles.

deuterium excess. We cannot, however, exclude that the slope inferior to 8 in Gibraltar is in fact a mixing line such as the one defined above, joining a pole of Mediterranean water vapour to a pole of Atlantic water vapour.

4.2. Isotopic composition of precipitation and local runoff in the Sierra de Gador

Cruz-San Julian et al. (1992) and Vallejos et al. (1997) discuss the isotopic signature of a single event in April 1990 (yielding between 7 and 15 mm rainfall) sampled along an altitudinal gradient in the Sierra de Gador. These data are well aligned in a δD–δ^{18}O diagram on a regression line with a slope close to 8 (Fig. 3). The mean deuterium excess of the water samples is about +15‰. Such a value is in agreement with the western Mediterranean origin of the rain baring fronts interpreted from weather maps by the authors. While meteoric water lines with deuterium excess values higher than +20‰ are characteristic for precipitation in the eastern Mediterranean basin, the kinetic isotopic effect in the western Mediterranean region is weaker and the deuterium excess values in precipitation are around +15‰ (Gat and Carmi, 1970). The good correlation of δ^{18}O with altitude

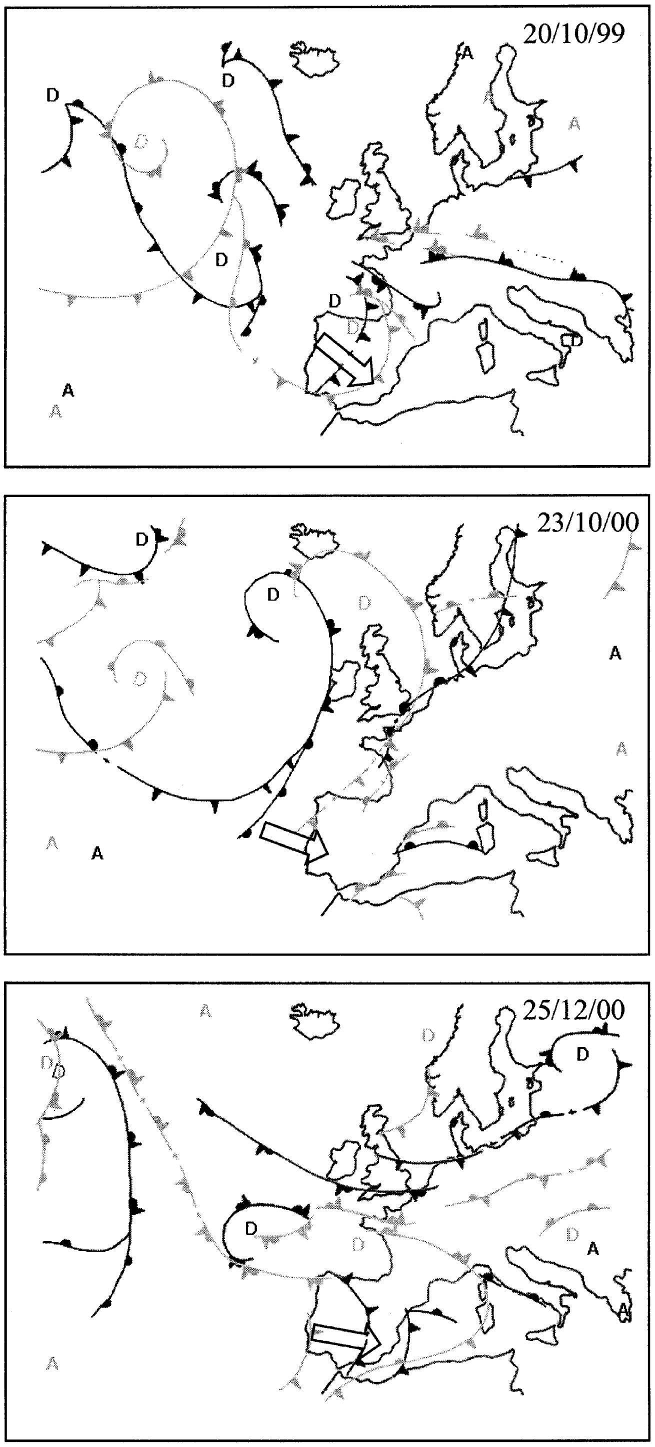

Fig. 5. Schematic weather maps showing the Atlantic origin of the three major rainfall events that produced runoff. Two successive dates are given for each precipitation, the first one in black, the second in grey.

($R^2 = 0.65$) reported by Vallejos et al. (1997) shows that an orographic effect is present. The water vapour mass has been forced to ascend the slopes of the Sierra de Gador and this resulted in precipitation and an impoverishment in heavy isotopes of the rain with altitude. However, the complexity of the hydrologic situation cannot be appraised by the study of this single event, since the isotopic records from Gibraltar, the literature review by Lazaro et al. (2001) and the isotopic study of Celle-Jeanton et al. (2001) suggest the influence of the Mediterranean and Atlantic Ocean on isotopic composition of the rainfall in this region.

Runoff from impermeable surfaces such as rock outcrops and dirt roads occurs several times per year and is collected in closed reservoirs of traditional water harvesting systems (van Wesemael et al., 1998). Runoff samples from such reservoirs, distributed along an altitudinal gradient, are considered for their isotopic properties (Table 1). A close inspection of the fluctuations in water level for three runoff reservoirs indicates that the majority of rain events does not produce runoff (Fig. 4). Three major events of 76 mm on 20 October 1999, 40 mm on 23 October 2000 and 124 mm from 23 to 26 December 2000 have produced the bulk of the runoff stored in the reservoirs. The sharp peaks in the water level records of Era Vicario and El Calabriar reservoirs indicate that during these events a large proportion of the runoff could not be stored. The excess runoff was evacuated through an overflow in the reservoirs opposite to the entrance (Fig. 4). Therefore, we can consider that the water previously stored in the reservoirs was replaced by these events. During the summer months, the water level drops in steps as a result of watering livestock. The nearly constant water level with occasional sharp declines indicates that water losses as a result of evaporation and/or leaks are limited. Weather maps for the rainfall of 20 October 1999, 23 October 2000 and 24–26 December 2000 demonstrate a high pressure cell over the Azores and depressions over the British Isles. This indicates a strong NW circulation, bringing air masses from the North Atlantic (Fig. 5). Therefore, the reservoirs can be assumed to contain runoff from precipitation with an Atlantic origin during both sampling campaigns. Isotopic analysis confirms such an Atlantic origin (Fig. 3). Runoff water is aligned in a δD–δ^{18}O diagram along a slope close to 8 (7.90 with $R^2 = 0.92$; Fig. 3). Most of the points are very close to the global meteoric water line (GMWL), i.e. have a deuterium excess close to +10‰. Furthermore, no correlation was found between the isotopic composition of the runoff water and its altitude. Therefore, one could assume that the cloud systems at the origin of the precipitation were not forced to ascend the slopes of the Sierra de Gador. Probably high altitude clouds have produced rain over the entire area. Such conditions do not allow to determine the dominant altitudinal zones for aquifer recharge (Vallejos et al., 1997). The alignment of the samples on a slope close to 8 indicates that the precipitation was not subjected to evaporation, either during their travel to the ground surface, as runoff on the soil surface or during their storage in the covered reservoirs.

4.3. Isotopic composition of waters from springs and boreholes

We will now discuss groundwater isotopic properties on a transect from the Sierra de Gador into the Campo de Dalias (Fig. 1 and Table 1). This category contains shallow groundwater from springs on the southern slopes of the Sierra de Gador (400–970 m asl) and deep groundwater from boreholes (pumped from 200 to 900 m depth) located on two North–South transects in the Campo de Dalias and piedmont between 70 and 343 m in altitude. Since the δ-values of the groundwater of the springs and boreholes are well aligned (Fig. 3), we could assume that, as suggested by the hydrogeological surveys of Pulido-Bosch et al. (1993) and Vallejos et al. (1997), the carbonate aquifer systems in the Campo de Dalias are connected to the outcrops in the Sierra de Gador. The groundwater samples are aligned in a δD–δ^{18}O diagram on a slope lower than 8 (6.58 with $R^2 = 0.99$; Fig. 3). In general, a slope between 3.9 and 8 indicates evaporation (Gonfiantini, 1986), and the slope gradient for the groundwater samples falls within this range. The validity of such an evaporation line, often used to interpret the origin of groundwater in semi arid regions (e.g. Davisson et al., 1999), can, however, be questioned in a karstic region. Rain water of Atlantic origin and rain water of Mediterranean origin, both of which have been shown to occur in this area, are not necessarily mixed to constitute the groundwater reservoir in limestones. It has been

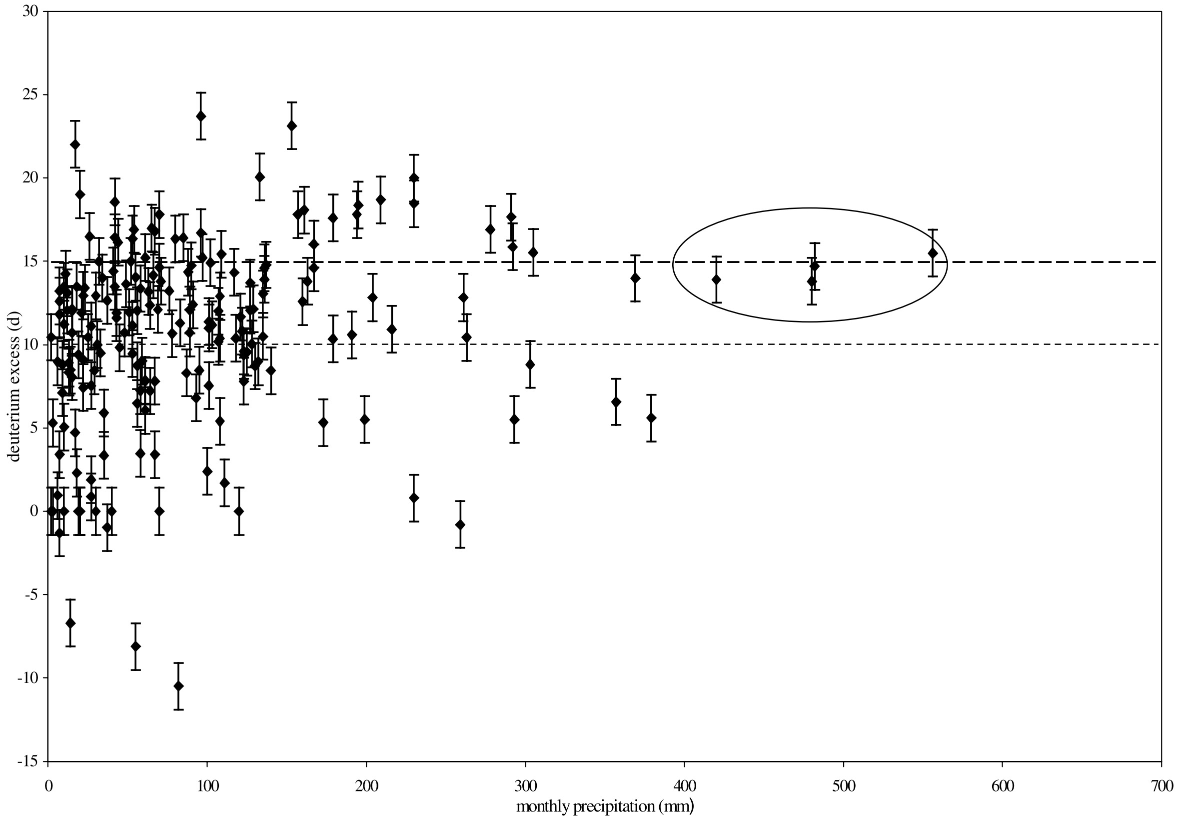

Fig. 6. Deuterium excess versus monthly precipitation in Gibraltar (from GNIP data; IAEA/WMO, 2001). Deuterium excess values of +10‰ (GMWL, dotted line) and of +15‰ (WMMWL, dashed line) are indicated.

shown by Pulido-Bosch et al. (1993) that the geology of the area is complex and that discontinuities are abundant (Fig. 1). Given the fact that residence times for groundwater are likely to be spatially variable, infiltrating rainwater with an Atlantic signature can coexist with infiltrating rainwater with Mediterranean origin. In such a situation, interpreting the regression line with a slope lower than 8 drawn through the boreholes and springs samples as a result of evaporation would not be correct. Moreover, the evaporation hypothesis assumes a purely Mediterranean origin for the rainfall, and this is also unlikely, since our investigation on local runoff has shown the dominance of rain water of purely Atlantic origin reflected in local runoff from two recent storms (Fig. 5). These samples are aligned on the GMWL and some of them are very close to samples of springs and boreholes having the least negative δ-values. The lack of connectivity within the aquifer is also suggested by the spatial distribution of typical Atlantic and Mediterranean poles within the aquifer system. An Atlantic signature prevails in shallow groundwater from springs on the slopes of the Sierra de Gador (Figs. 1 and 3). These springs are concentrated in zones with a relatively large annual precipitation (orographic rainfall effect demonstrated by Lazaro and Rey (1991)) and apparently short residence times, since their isotopic signature is very close to that of recent storms. Therefore, the spring water reflects the Atlantic character of the largest rainfall events during the previous year (Fig. 3). The recharge of shallow groundwater in the Sierra de Gador by Atlantic rainfall is in agreement with the findings of Cruz-San Julian et al. (1992). In contrast, the deep groundwater from boreholes generally has a Mediterranean signature. Apparently, the recent rainfall events (return period of the 20 October 1999 event was 1.23 yr) have not produced large enough quantities of recharge to make a significant contribution to the isotopic signal of the deep groundwater reservoir in the Campo de Dalias. One can assume two pathways for the precipitation to reach the deep groundwater reservoirs in the Campo de Dalias: (i) infiltration in the recharge zone in the Sierra de Gador followed by lateral percolation through the carbonates or (ii) infiltration in the Campo de Dalias and vertical percolation through the Mio-Pliocene sediments that cover the Carbonatic aquifer (Fig. 1). Both pathways require large quantities of rainfall that will probably only occur during extreme events. During such events, either connectivity between the recharge zone and the reservoirs is established and/or direct percolation through the Mio-Pliocene sediments does reach the deep groundwater reservoir. The hypothesis of extreme events with a dominantly Mediterranean signal recharging the deep groundwater is strengthened by the results of other isotopic studies in the region. A closer inspection of the GNIP precipitation data from Gibraltar reveals that extreme rainfall (>400 mm in a single month) tends to be characterised by a Mediterranean signature as expressed by their deuterium excess (Fig. 6). Whereas Celle-Jeanton et al. (2001) demonstrated that heavy rainfall in the south of France has a Mediterranean signature based on their δ^{18}O values. The isotopic depletion of Mediterranean groundwater could be explained by the depletion of the water vapour content of the air masses during extreme rainfall (Ciais and Jouzel, 1994).

5. Conclusion

In the karstic area of southeastern Spain analysed here, different groundwater samples show differences in their distribution in a δD–δ^{18}O diagram as well as in deuterium excess. These differences are related to the contrast existing between water vapour of Atlantic origin reflected in local runoff and shallow groundwater and water vapour of western Mediterranean origin dominant in deep groundwater. Firm conclusions on the causes of this spatial pattern cannot be drawn at this stage, although the dominant Mediterranean signal of extreme rainfall events is in agreement with the Mediterranean character of large reservoirs with long residence times. The fact that groundwaters from places 5 km apart, aligned on a mixing line in a δD–δ^{18}O diagram, have very different deuterium excess values means that spatial and temporal discontinuities play a major role in recharging the hydrological system. In such a case, the deuterium excess signature can provide a useful tool for analysing in detail the characteristics of the recharge. A slope lower than 8 in a δD–δ^{18}O diagram must not be, in such a situation, interpreted as the influence of evaporation.

Acknowledgments

This research was supported by a NATO Collaborative Linkage Grant CLG 974970. This support is gratefully acknowledged. The weather maps were kindly supplied by Météo-France. The comments of Dr J. Mudry and of an anonymous referee were very helpful in improving the manuscript.

References

Ayalon, A., Bar-Matthews, M., Stass, E., 1998. Rainfall–recharge relationships within a karstic terrain in the Eastern Mediterranean semi-arid region, Israel: δ^{18}O and δD characteristics. Journal of Hydrology 207, 18–31.

Cara, L., Rodriguez, J.M., 1989. El Ambito Economico del pastoralismo Andalusi. Grandes aljibes ganaderos en la provincia de Almeria. In: Cara, L., (Ed.), El Agua en Zonas Aridas: arqueologia e historia, I Coloquio de Historia y Medio Fisico, vol. 633–653. Instituto de Estudios Almerienses, Almeria, p. 1149.

Celle-Jeanton, H., Travi, Y., Blavoux, B., 2001. Isotopic typology of the precipitation in the Western Mediterranean region at three different scales. Geophysical Research Letters 28, 1215–1218.

Ciais, P., Jouzel, J., 1994. Deuterium and oxygen 18 in precipitation: isotopic model, including mixed cloud processes. Journal of Geophysical Research 99, 16793–16803.

Cruz-San Julian, J., Araguas, L., Rozanski, K., Benavente, J., Cardenal, J., Hidalgo, C., Garcia-Lopez, S., Martinez-Garrido, J.C., Moral, F., Olias, M., 1992. Sources of precipitation over South-Eastern Spain and groundwater recharge. An isotopic study. Tellus 44B, 226–236.

Davisson, M.L., Smith, D.K., Kenneally, J., Rose, T.P., 1999. Isotope hydrology of southern Nevada groundwater: stable isotopes and radiocarbon. Water Resources Research 35, 279–294.

Gat, J.R., Carmi, I., 1970. Evolution of the isotopic composition of atmospheric waters in the Mediterranean Sea area. Journal of Geophysical Research 15, 3039–3048.

Gonfiantini, R., 1986. Environmental isotopes in lakes studies. In:

Fritz, P., Fontes, J. (Eds.), Handbook of Environmental Isotope Geochemistry, the Terrestrial Environment, vol. 2B. Elsevier, Amsterdam, pp. 113–168.

IAEA/WMO, 2001. Global Network for Isotopes in Precipitation. The GNIP Database. Accessible at http://isohis.iaea.org.

Jouzel, J., Merlivat, L., 1984. Deuterium and oxygen-18 in precipitation: modelling of the isotope effects during snow formation. Journal of Geophysical Research 89, 11749–11757.

Kattan, Z., 1997. Chemical and environmental isotope study of precipitation in Syria. Journal of Arid Environments 35, 601–615.

Lazaro, R., Rey, J.M., 1991. Sobre el Clima de la Provincia de Almeria (SE Iberico): primer ensayo de catografia automatica de medias anuales de temperatura y precipitacion. Suelo y Planta 1, 61–68.

Lazaro, R., Rodrigo, F.S., Gutierrez, L., Domingo, F., Puigdefabregas, J., 2001. Analysis of a 30-year rainfall record (1967–1997) in semi-arid SE Spain for implications on vegetation. Journal of Arid Environments 48, 373–395.

Pulido-Bosch, A., Martin Rosales, W., Vallejos, A., Molina, L., Navarrete, F., de Simon, E., 1993. The Southern Catchment area of the Sierra de Gador and its impact n the Campo de Dalias. In: Pulido-Bosch, A., (Ed.), Some Spanish Karstic Aquifers, Universidad de Granada, pp. 159–181.

Pulido-Bosch, A., Pulido-Beboeuf, P., Molina-Sanchez, L., Vallejos, A., Martin-Rosales, W., 2000. Intensive agriculture, wetlands, quarries and water management. A case study (Campo de Dalias, SE Spain). Environmental Geology 40, 163–168.

Tout, D., 1990. The horticulture industry of Almeria Province, Spain. The Geographical Journal 156, 304–312.

Vallejos, A., Pulido-Bosch, A., Martin-Rosales, W., Calvache, M.L., 1997. Contribution of environmental isotopes to the understanding of complex hydrologi systems. A case study: Sierra de Gador, SE Spain. Earth Surface Processes and Landforms 22, 1157–1168.

van Wesemael, B., Poesen, J., Solé Benet, A., Cara Barrionuevo, L., Puigdefabregas, J., 1998. Collection and storage of runnoff from hillslopes in semi-arid environment: geomorphic and hydrologic aspects of the aljibe system in Almeria Province, Spain. Journal of Arid Environments 40, 1–14.