Origin and Type of Rainfall for Recharge of a Karstic Aquifer in the western Mediterranean, a Case Study from the Sierra de Gador-Campo de Dalias (south-east Spain).

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Résumé
L'excès en deutérium (d) est étudié afin de préciser le contexte isotopique de l'aire d'étude : Campo de Dalias et la Sierra de Gador (province d'Almería). Les précipitations du site d'étude sont dominées par deux influences climatiques majeures : l'océan atlantique (d = 10‰) et de l'ouest du bassin méditerranéen (d = 15‰). Les évènements pluvieux extrêmes ont une influence méditerranéenne plus affirmée, ceux ci dominent la recharge de la nappe aquifère qui possède une valeur de d de l'ordre de 13,6‰. Les précipitations rechargeant la nappe aquifère possèdent une période de retour comprise entre 0,9-4,9 années. Alors que les épisodes pluvieux modérés, plus fréquents sont sous représentés dans la nappe et correspondent à 60-90% du total précipité sur une année.

Introduction

Like many Mediterranean regions and semi-arid area, the Campo de Dalias (Almeria province, southeast Spain) is suffering from large increases in the use of groundwater from its major aquifers. Hence, the study of the recharge patterns of this aquifer is of a major economical and environmental interest. The Sierra de Gador is a mountain range reaching 2242 m asl and the Campo de Dalias is the connected coastal platform. Several authors have discussed the complexity and the scale of the recharge system of the Campo de Dalias and the carbonate mountain range of the Sierra de Gador aquifers (e.g Pulido-Bosch et al., 1993; Molina et al., 2002).

The deuterium excess (d= D-8 ^{18}O) reflects the relative humidity and the air temperature of the region where the evaporation leading to rainfall occurred (Gonfiantini, 1996, Jouzel, 1986, Vandenschrick et al., 2002). In regions with contrasting origins of precipitation (Atlantic ocean and Mediterranean sea), d-value could be linked to weather patterns, which generated the precipitation. The deuterium excess could be used to determine the origin of precipitation and in which proportion rainfall from different origins contribute to recharge of the aquifer (Vandenschrick et al., 2002, Lee et al., 1999).

The objective of this paper is to better define the recharge patterns of karstic aquifer by using the regional isotopic signal of precipitation, to demonstrate the occurrence of preferential recharge during heavy rainfall and to determine a threshold to characterise such events.

Methodology

Isotope signatures in precipitation from the Global Network for Isotopes in Precipitation (GNIP) and literature data are compared with isotopic data from aquifer of the study area to explain the origin and type of precipitation events dominating recharge. In order to detect regional trends in *d*-values with precipitation, the latter had to be standardised across sampling stations with the index for extreme events Ie (Conte et al., 2002) which is defined as the rainfall divided by twice the long-term rainfall of the rainiest month of the station. Due to the strong precipitation gradient with altitude in the Sierra de Gador-Campo de Dalias aquifer system, the return period of the monthly rainfall was calculated for a meteorological station (data covering the period 1961 to 1995) situated at the middle range of the Sierra de Gador (1210 m asl).

Results and discussion

The weighted annual mean *d*-values of precipitation recorded in GNIP stations within the Mediterranean basin show a distinct spatial pattern. The *d*-values in the western part considered as a mixing zone is between 10‰ and 15‰ and falls between typical values for water vapour of Atlantic origin (*d*=10‰), and the eastern Mediterranean represented with *d*=22‰ (Celle-Jeanton et al., 2001a; Vandenschrick et al., 2002). The weighted mean monthly *d*-values will be used to determine whether a relationship exists between the origin of the water vapour and the amount of precipitation. Weighted mean *d*-value for the GNIP stations on the Iberian peninsula were calculated for months with rainfall of over 100 mm and over 150 mm (Table 1). For all stations except Faro, it can be observed that more rainy months enrich the weighted mean *d*-values and therefore, it can be assumed that the heavy storms have a Mediterranean origin (Celle-Jeanton et al., 2001a).

Table 1: Weighted mean d-value (‰) of precipitation for the western Mediterranean.

GNIP Station	Measurement period	Weighted mean d-value (‰) *(number of data)*	Weighted mean d-value (‰) Rainfall >100 mm *(number of data)*	Weighted mean d-value (‰) Rainfall >150 mm *(number of data)*
PORTALEGRE	1988 - 1999	13.14 (*106*)	13.61 (*29*)	13.62 *(15)*
FARO	1978 - 2001	11.68 (*118*)	12.00 (*25*)	11.94 *(10)*
GIBRALTAR	1961 - 2001	11.95 (*188*)	12.21 (*71*)	12.72 *(36*)
BARCELONA	1985 - 1982	11.76 (*70*)	13.31 (*11*)	13.92 *(3*)
GENOA	1961 - 2001	9.87 (*308*)	10.37 (*111*)	10.67 (66)
TUNIS	1968 - 1998	9.64 (*178*)	12.59 (*24*)	14.07 (9)

The study area was considered to be dominated by the weather systems of the south-eastern coast of the Iberian peninsula represented by the GNIP Stations of Faro, Gibraltar and Barcelona which follow the same trend (RMSE = 0.38%) and their *d*-value is about 12‰.

Some events were sampled in the Sierra de Gador. The mean *d*-value for precipitation in April 1990 was about 15‰ (Vallejos et al., 1997) and 15.8‰ for the snow in January 2001 (Vandenschrick, 2002). These values, indicating a western Mediterranean origin. The local runoff (*d*-value=10.6‰) included three Atlantic storms in October 1999 (Vandenschrick et al., 2002), which was sampled from traditional water harvesting systems (van Wesemael et al., 1998). Deep groundwater within the Campo de Dalias and the Sierra de Gador has a *d*-value ranging from 11.4‰ to 15.1‰, and an average of 13.6‰. The mean *d*-value of shallow groundwater in the Sierra de Gador is on average 12.1‰. The latter value is between the *d*-value of the precipitation (10.6‰) and the *d*-value for deep groundwater. This points to percolation of precipitation into local perched water tables in the Sierra de Gador. Vandenschrick et al. (2002) demonstrated that within a karstic aquifer system water with different isotopic signatures can co-exist. The monthly weighted *d*-value for the south and

east coast of the Iberian peninsula (with *d* :11.81 ± 0.38‰) is substantially lower than the *d*-value of the deep groundwater (13.6‰) and a better match between *d* from precipitation and groundwater would be obtained when only extreme events would be considered. The mean weighted *d*-values for Gibraltar, Barcelona and Faro were calculated over monthly rainfall depth intervals. The isotopic data from Faro show a typical Atlantic signature, the *d*-value always being below 12.5‰ (Table 1) and they are excluded because they can not be compared to the *d*-value of the deep groundwater (13.6‰). The *d*-values of Gibraltar and Barcelona increase significantly with precipitation. Barcelona and Gibraltar show both an isotopic influence from the Atlantic and the Mediterranean. Due to the location of the study area, it is supposed that its isotopic influence is between that of Barcelona and Gibraltar. The *d*-values of the groundwater in the study area (13.6‰) should be related to a value for the Index of extreme events (Ie) above which the bulk of the recharge would have occurred. A monthly rainfall with an Ie between 0.7 (Barcelona) and 1.4 (Gibraltar) indicates the importance of extreme events in recharging the aquifer and has a return period of 0.9-4.9 years in the sierra de Gador. The volume of the monthly rainfall, corresponding to this return period equals 115 to 216 mm. Months with a rainfall of more than 115 mm are rare in the sierra de Gador, where only 25 of such months have been registered from 1961 to 1995 and only five months with more than 216 mm. It is well known that the isotopic signature of groundwater resembles the weighted mean rainfall input (Darling, 2004). Using the La Zarba rainfall data, the recharge is restricted to only a maximum of 37 % of the total rainfall volume for the period 1961 to 1995. Obviously, this is an average for the entire catchment area, and does not preclude that due to the strong altitudinal gradient in precipitation, local recharge forms a more important part of the water balance. Springs draining perched aquifers can react more quickly as demonstrated by their lower *d*-values (12.1‰) following winter rains with an Atlantic signature (*d*=10.6‰).

Conclusions

The analysis of deuterium excess (*d*) in precipitation of stations in the GNIP network around the Mediterranean basin allowed us to characterise the origin and type of precipitation in the western Mediterranean. Two main sources of precipitation, the Atlantic Ocean and the western Mediterranean were identified in the literature. For the southern and eastern coast of the Iberian peninsula an increase of *d*-values with precipitation volume was observed. This relationship could, however, not directly be applied to identify the recharge the large karstic aquifer system of the Sierra de Gador-Campo de Dalias, since the *d*-values in the aquifer exceed those of the weighted mean precipitation, suggesting that light and moderate rainfall does not contribute to recharge. A weighting of *d*-values starting with the extreme events and gradually including more moderate storms provides an estimate of the type of storms dominating recharge and their return period. The infrequent occurrence of these events (return period: 0.9-4.9 years) means that only a maximum of c. 37 % of the total precipitation contributes to recharge. Measures to increase recharge should primarily target deep percolation during moderate rainstorms. Concentration of local runoff on the hillslopes, followed by infiltration below the root zone could be an alternative, which should be further investigated.

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