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Recharge to mountainous carbonated aquifers in SE Spain: Different approaches and new challenges

J.M. Andreu [a], F.J. Alcalá [b,c], Á. Vallejos [d], A. Pulido-Bosch [d,*]

[a] Department of Earth Sciences and Environment, University of Alicante, AP 99, Alicante 03080, Spain
[b] Estación Experimental de Zonas Áridas, CSIC, Almería 04120, Spain
[c] Geo-Systems Centre/CVRM, Instituto Superior Técnico, Lisbon 1049-001, Portugal
[d] Department of Hydrogeology, University of Almería, Almería 04120, Spain

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ABSTRACT

As in most semiarid regions, the main source of freshwater in SE Spain is its aquifers, and their exploitation has enabled the development of highly profitable irrigated agriculture and tourism industries. The application of sustainable water management plans requires aquifer recharge to be quantified and its spatial pattern evaluated. This paper gives a comprehensive review of various recharge studies in mountainous carbonated aquifers, the most important groundwater reservoirs in SE Spain. Quantification of potential recharge rates and their spatial variability are illustrated using satellite-based modeling and tracer techniques. Actual recharge figures from the application of a lumped model based on water table fluctuations are also presented. Potential recharge relative to actual recharge is around 1 in small aquifers and flat areas and may increase up to 1.3 in heterogeneous mountainous aquifers with deep water levels due to losses of recharge in transit in the vadose zone. The complex interaction between climate, geology, aquifer geometry, topography, soil properties and the degree of karstification prevents the systematization of any particular technique to quantify potential recharge. The use of water table fluctuation methods for actual recharge evaluation requires daily time steps to compute unnoticed small recharge events. Therefore, the monitoring of environmental variables and the use of complementary techniques for comparison are recommended. Despite their importance for the correct assessment of recharge in the region, uncertainty analyses are still scarce, and the natural variability of recharge is unknown in most cases. Effort is required to improve the spatial and temporal characterization of recharge through the integration of interdisciplinary sciences.

1. Introduction

As in other arid and semiarid regions in the world, the scarcity and unpredictability of rainfall events and the lack of perennial rivers mean that aquifers are the main source of water resources in SE Spain (mostly Almería, Murcia and Alicante provinces, Fig. 1). The exploitation of aquifers has enabled the development of highly profitable irrigated agriculture and tourism sectors in the region (Pulido-Bosch et al., 2000; Bellot et al., 2007; Molina et al., 2009). Agriculture in the region supplies ~20% of Spain's total Gross Value Added supplied by this sector, accounting for more than 80% of the total water demand in the region and as much as 85% in some counties (Campo de Dalías, Campo de Cartagena, Altiplano de Murcia and Alto Vinalopó). Groundwater resources also meet an important fraction of the urban water demand: approximately 52% of urban supply in the province of Alicante (~2 million inhabitants) is supplied from aquifers.

Aquifer overexploitation is closely associated with the main centres of tourism and agricultural development. Nowadays, most of the groundwater bodies in semiarid SE Spain are considered overexploited or at risk (MMA, 2006). This situation has been partially triggered by weak administrative control on pumping rates and the limited understanding of the hydrogeological functioning of those aquifers. Environmental and social impacts have resulted from various groundwater processes, including salinization induced by seawater intrusion in coastal areas or by confined brines in some inland aquifers (Sánchez-Martos et al., 2007); land subsidence in alluvial aquifers (Mulas et al., 2003); groundwater pollution in irrigated areas (Pulido-Bosch et al., 2000); and desiccation or critical damage to wetlands and groundwater-fed ecosystems (Robledano et al., 2010).

* Corresponding author. Tel.: +34 950015465.
E-mail address: apulido@ual.es (A. Pulido-Bosch).

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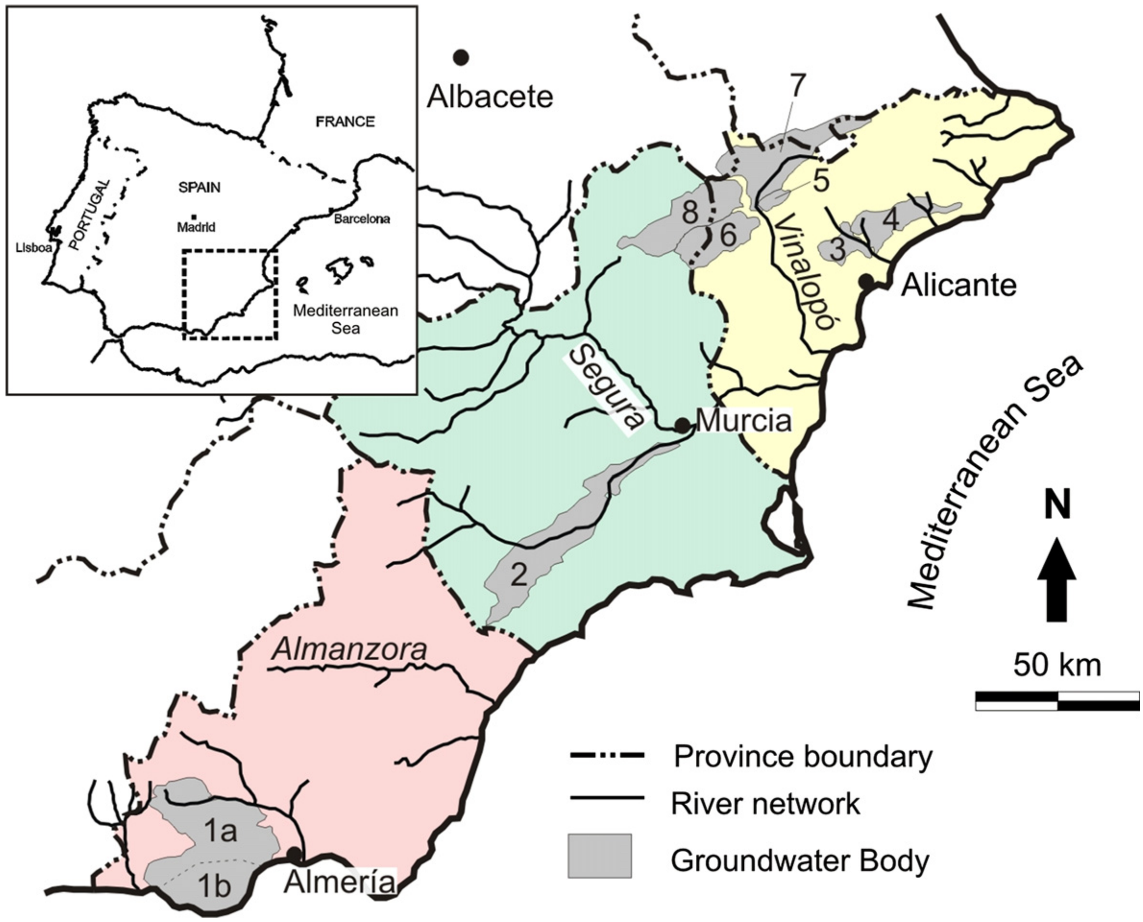

Fig. 1. Location map with provinces - Almería (red), Murcia (green), Alicante (yellow) -, main river network (river names in italics) and groundwater bodies with recharge studies cited in the text. Groundwater Bodies: 1. Sierra de Gádor (1a) – Campo de Dalías (1b); 2. Guadalentín; 3. Agost – Monnegre (covering the Ventós aquifer); 4. Orcheta (covering the Cabeçó d'Or aquifer); 5. Peñarrubia; 6. Serral – Salinas; 7. Villena – Benejama (covering the Solana aquifer); 8. Jumilla – Yecla. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Before 2000, most recharge studies in SE Spain were undertaken by national or local agencies in the context of hydrological management plans (HMPs), with only a few studies being undertaken by universities and research institutes. Recharge in the HMPs was usually computed as a steady average rate from which advisable pumping rates could be established (MMA, 2000). However, such estimates are subject to great uncertainty because of the imprecision involved in defining the geometry of a groundwater body or because of other important particularities of SE Spain: wide temporal and spatial variability in rainfall and complex topography and geology were not taken into account. When the EU-Water Framework Directive (2000/60/EC) came into force in December 2000, fundamental research became a critical prerequisite for increasing the accuracy of groundwater resource assessment and control (Mostert, 2003; MMA, 2006). Effective groundwater management especially requires the identification of the mechanisms of recharge generation (e.g. diffuse vs. focused), the evaluation of the uncertainties in recharge estimation, the spatiotemporal assessment of recharge patterns, and the integration of groundwater studies with other scientific disciplines.

This paper aims to illustrate the application of different techniques for estimating and mapping recharge in some representative carbonated aquifers of SE Spain. An overall description of advantages and limitations is given, and the hydrological meaning of estimates is pointed out. To quantify and map recharge in Sierra de Gádor, a mountainous carbonate massif in the Almeria province, different complementary approaches were applied: a) a satellite-based approach that supplies spatially-distributed potential recharge estimates; b) an atmospheric chloride mass balance to evaluate potential recharge in transit to the water table; and c) an isotopic analysis to trace the impact of altitude in recharge generation. The usefulness of physically-based techniques in the saturated zone for groundwater modeling was explored in several aquifers in the Alicante province. There, actual recharge values estimated from water table fluctuations and pumping rates were used to calibrate a numerical-modeling tool for estimating actual recharge rates from meteorological variables (rainfall and potential evapotranspiration) and aquifer parameters.

2. Study region

In SE Spain, an area close to 23 000 km^2 is under the influence of a semiarid climate (Fig. 1). Winters are moderate in temperature and relatively humid, and summers are very dry and hot. Mean annual precipitation ranges between 200 mm in the lowlands to 650 mm in the mountains. Rainfall generation is mainly controlled by Atlantic weather fronts, but Mediterranean convective systems of short duration and high intensity are common during the summer. Mean annual temperatures range between 10 °C in the mountains and 18.5 °C on the coastal fringe. Insolation is high, more than 3300 h per year in some low-lying places, while potential evapotranspiration is 800–1200 mm/year. Agricultural land occupies 45% of the total area, 21% is sparsely vegetated (steppes and badlands), 18% is covered by woodland and shrublands, and 6% is forest (EEA, 2002), the remaining 10% being urban areas.

SE Spain belongs to the eastern Betic Cordillera, an Alpine chain that is divided into two main domains: the Internal and the External Zones. The Internal Zone consists of three tectonic complexes: the Nevado-Filabride Complex (consisting of medium to high grade metamorphic rocks), the overlying Alpujarride Complex (characterized by low to medium grade Paleozoic-to-Triassic metamorphic rocks), and the uppermost Malaguide Complex (consisting mainly of an unmetamorphosed complex) (Vera, 2004). The External Zone consists of Mesozoic and Tertiary rocks representing the continental margin of the Iberian Plate.

From a hydrogeological point of view, the varied geology of the eastern Betic Cordillera may be classified into four lithological groups with different hydraulic behaviours:

(1) Triassic carbonate formations belonging to the Alpujarride and Malaguide Complexes plus Jurassic to Cretaceous carbonate formations of the External Zone, forming moderately to highly permeable aquifers, with unsaturated zones of 100 to more than 1000 m in thickness. Natural recharge comes from rainfall, while discharge occurs through springs and pumped abstractions. The aquifers included in this study fall into this first lithological group.
(2) Weathered and fissured metapelitic formations (mainly phyllite, micaschist, and interbedded quartzite) belonging to the Nevado-Filabride, Alpujarride and Malaguide Complexes. These form low-moderate permeability aquifers of local significance and reduced thickness, although locally they may be productive.
(3) Large Tertiary sedimentary basins made up of highly permeable layers of conglomerate and calcarenite more than 100 m in thickness and partially confined in the central sectors by wide marly formations. They constitute large aquifer systems of high productivity and reserves. Their main inputs are diffuse recharge and infiltration in stream beds.
(4) Quaternary and Plio-Quaternary alluvial and colluvial beds, deltas and piedmonts are phreatic aquifers of high-moderate permeability with variable thickness (a few to hundreds of metres). Recharge is mainly from lateral inflow, diffuse recharge, irrigation and urban returns, whilst discharge is generally from pumped abstractions. They support wetlands and groundwater-fed ecosystems.

3. Recharge study cases: methods and results

Several techniques have been applied to estimate recharge in SE Spain. In general, local scales have been selected to investigate the suitability of different methods, while regional scales have been adopted for the assessment of water resources. The techniques can be classified (Lerner et al., 1990; Simmers et al., 1997; Scanlon et al., 2002) according to a) the zone from which data are taken (surface water and soil, unsaturated zone, and saturated zone) and b) the nature of the technique employed (physical, tracer, numerical-modeling, empirical). Surface water and soil and unsaturated zone approaches give values of potential recharge, i.e. the infiltrated water that may or may not reach the water table with different timing depending on the unsaturated processes or the capacity of the saturated zone to accept water. On the other hand, saturated zone approaches give results related to the actual recharge, i.e. the water that really reaches the water table. Another important distinction must be made between diffuse (direct) recharge over large areas and focused or localized recharge at particular sites (Lerner et al., 1990; Alcalá et al., 2011). The following sections present results from the application of several techniques to some important carbonated aquifers in SE Spain.

3.1. Using a satellite-based ecohydrological model to estimate potential recharge

The usefulness of satellite data for recharge studies was tested in Sierra de Gádor by Contreras et al. (2008). Based on the hydrological equilibrium hypothesis (Nemani and Running, 1989), which suggests that vegetation evapotranspires while minimizing water stress, they developed a spatially-distributed algorithm to compute long-term annual potential recharge (R) estimates as the residual of annual values of precipitation (P) and evapotranspiration (ET):

$$R = P - ET \tag{1}$$

Estimation of R by equation (1) assumes that surface runoff is negligible at the long-term scale, which can be partially valid in carbonated landscapes with a medium-high karstification degree. ET is spatially estimated through a novel algorithm that combines a spectral vegetation index ($NDVI$) and a monthly water budget model:

$$ET = (ET_{\max} - ET_{\min}) \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} + ET_{\min} \tag{2}$$

where $NDVI$ is the average long-term Normalized Density Vegetation Index observed at the pixel level, and the paired values ($NDVI_{\min}$, $ET_{\min}$) and ($NDVI_{\max}$, $ET_{\max}$) are referred to the $NDVI$ and ET values expected for two reference conditions, which must be previously defined according to the local mean annual rainfall (MAP) or a similar water availability index, e.g, Specht's evaporative coefficient (Specht and Specht, 1989). At the pixel level, $NDVI_{\min}$ (bare soil condition) and $NDVI_{\max}$ (vegetation cover close to its rainfall-based potential status) values can be empirically approached as the lower and upper boundaries of the MAP-$NDVI$ scatterplot extracted for a sample of pixels with no lateral surface and subsurface water inputs (Boer and Puigdefábregas, 2005). Alternatively, $ET_{\min}$ and $ET_{\max}$ reference values can be estimated using a monthly water budget model that integrates the average seasonal dynamics of climate (precipitation and potential evapotranspiration), the water retention capacity of the soil, and a coefficient that represents the mean annual evaporate conductance of vegetation (Specht and Specht, 1989).

The approach was first applied by Boer and Puigdefábregas (2005) in the upper reaches of the Guadalentín River Basin and later by Contreras et al. (2008) in the Sierra de Gádor Mountains (Fig. 2A).

In Sierra de Gádor, where surface runoff is almost negligible (less than 5% annual precipitation according to Frot and van Wesemael, 2009), average results obtained for 33 catchments covering an area of 552 km^2 indicated mean annual potential recharge values of 55, 75 and 100 Mm^3/year for dry, average and wet hydrological years (1 Mm^3 ≡ 1 Million m^3). These figures are equivalent to 29%, 31% and 35% of the MAP for mean annual precipitation observed for those yearly rainfall conditions. Because the model can be easily integrated into a GIS, the approach provides an interesting framework to explore changes of effective precipitation with altitude (Fig. 2B) and to identify potential sites for increasing recharge artificially (Contreras, 2006).

3.2. Using an atmospheric chloride mass balance to estimate potential recharge in transit

The atmospheric chloride mass balance (CMB) (Eriksson and Khunakasem, 1969; Custodio et al., 1997) is one of the most widely-used techniques for estimating recharge in arid and semiarid

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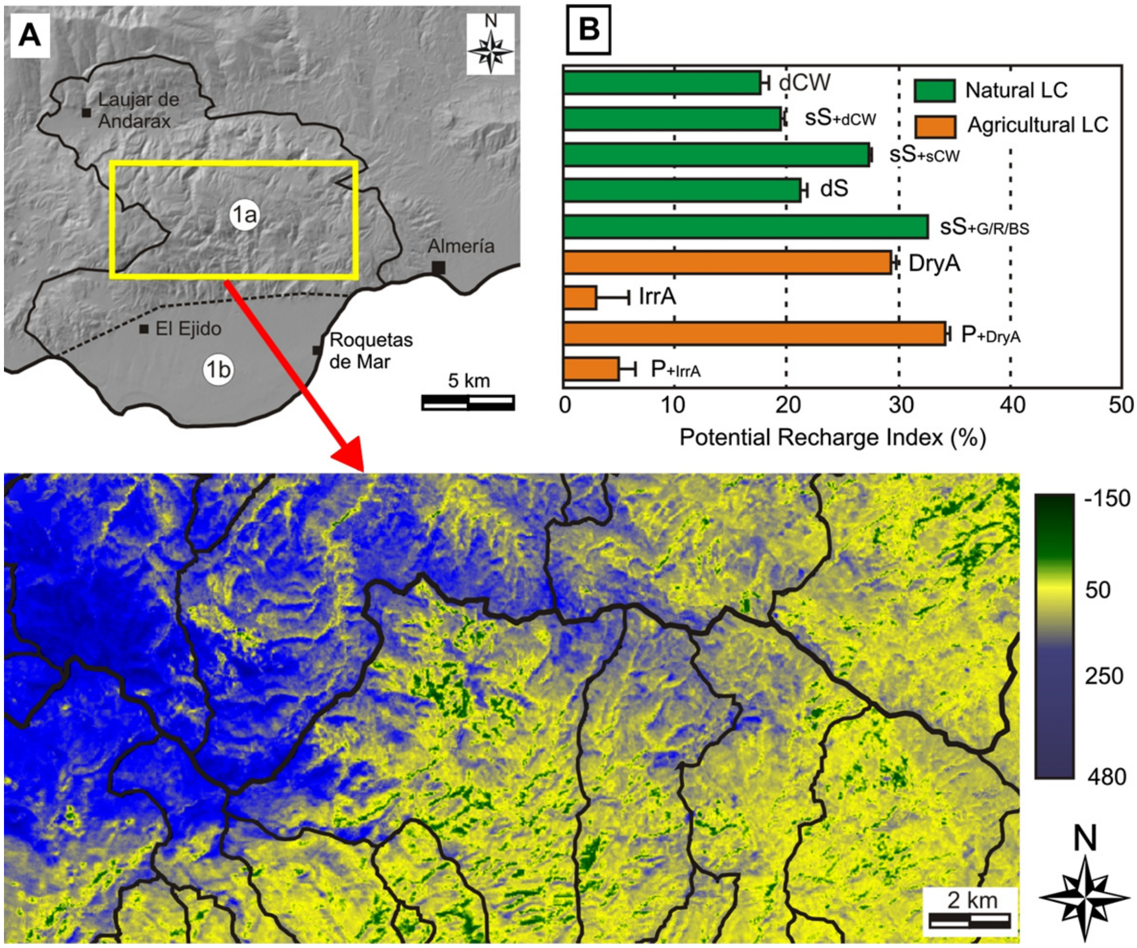

Fig. 2. (A) Spatial distribution of potential recharge (mm year^{-1}) estimated for a grid in Sierra de Gádor (dashed box in the upper-left figure) using the satellite-based ecohydrological model developed by Contreras et al. (2008). (B) Potential recharge index (ratio between mean annual values of potential recharge and precipitation) estimated for different land cover (LC) types (Contreras, 2006): dCW coniferous woodland (high density); sS + dCW sparse shrubland mixed with dense patches of conifers; sS + sCW sparse shrubland mixed with sparse patches of conifers; dS shrubland (high density); sS + G/R/BS sparse shrubland with patches of grass/rock/bare soil; DryA dryland agriculture (olive and almond trees); IrrA irrigated agriculture (citrus trees); P + DryA pastures mixed with dryland agriculture; P + IrrA pastures with patches of irrigated agriculture. Numbers in (A) correspond to the groundwater body units in Fig. 1.

regions in both unsaturated and saturated zones (Scanlon et al., 2002). For long time periods and under steady atmospheric and land use conditions, with no external contributions of chloride except precipitation, the CMB in the unsaturated zone should be, accordingly:

$$P \cdot C_P = R \cdot C_R + U \cdot C_U + \Delta\theta \cdot C_\theta \tag{3}$$

where P, R, U and $\Delta\theta$ are the precipitation, total (diffuse plus concentrated) potential recharge in transit to the water table, surface runoff, and soil moisture change during the sampling period, respectively, all in mm, and C is the average chloride concentration during the sampling interval for P or the average concentration from a specific number of samples in the period for R, U and θ (specified by the subscripts), both in mg L^{-1} $\equiv$ g m^{-3}.

R is the unknown variable to be deduced once the atmospheric bulk chloride deposition ($A_P = P \cdot C_P$), the chloride export flux by runoff ($A_U = U \cdot C_U$), the change of chloride mass flux in the unsaturated zone ($\Delta\theta \cdot C_\theta$), and C_R are measured. U is computed from runoff gauging stations and $\Delta\theta$ from daily soil moisture records at experimental sites (Fig. 3). Equation (3) can be simplified when the CMB is applied to long periods of time in which changes in the chloride flux in the unsaturated zone and produced by surface runoff can be considered negligible. Both conditions are easily reached in carbonated mountainous areas, as pointed out by Frot and van Wesemael (2009) ($U < 0.05P$) and Cantón et al. (2010) ($\Delta\theta \sim 0$) for the Sierra de Gádor Mountains. Correct estimates of A_P (which must include both wet and dry atmospheric deposition components) are critical for reducing the uncertainty in estimates of R (Alcalá and Custodio, 2008a). Because C_R is the chloride content routed through the unsaturated zone down to the water table, its value is preferably measured in water samples collected from shallow, perched aquifers or from shallow wells and boreholes using chemical and isotopic tracers to distinguish groundwater in which Cl derives only from atmospheric sources (Alcalá and Custodio, 2008b).

The CMB method was applied to the southern versant of the Sierra de Gádor-Campo de Dalías aquifer system (Fig. 3) to evaluate potential recharge in transit by sampling local, shallow perched aquifers (Alcalá et al., 2011). The abrupt relief of this coastal region and the negative A_P gradient towards the summit (between 0.5 and 1 g m^{-2} year^{-1} km^{-1}) induce a large reduction in C_R along the slope (Fig. 3a). In accordance with the linear mixing models of recharge produced at different elevations defined by Custodio et al. (1997), Alcalá et al. (2007) regionalized yearly R from A_P data and C_R values for the average 2003/04 and the dry 2004/05 hydrological

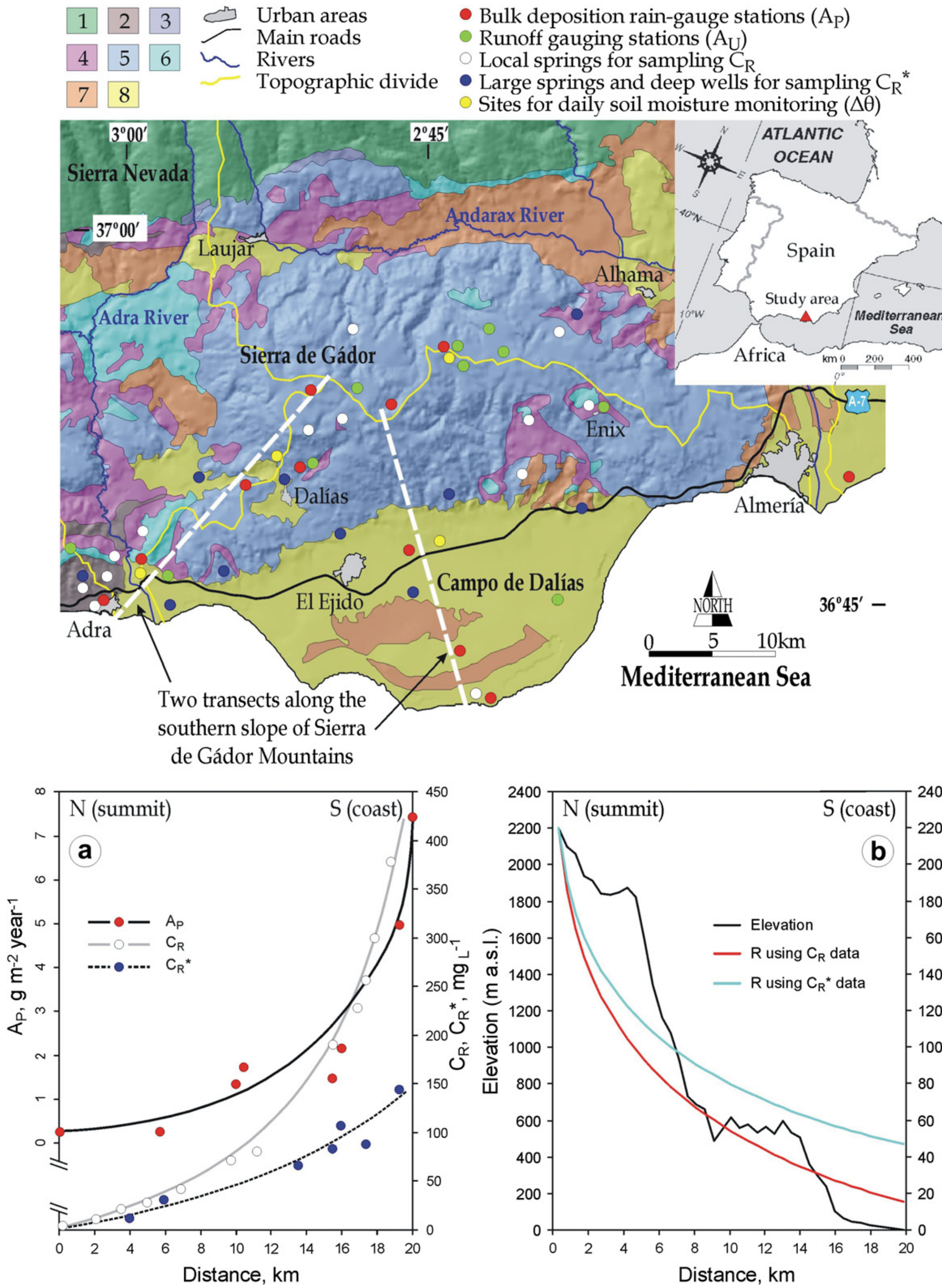

Fig. 3. Estimate of recharge in transit in a north–south transect (N = summit at distance 0; S = coast at distance 20 km) along the southern slopes of the Sierra de Gádor-Campo de Dalías aquifer system (GWB number 1a–1b in Fig. 1) for the average and dry rainfall periods 2003/04 and 2004/05, respectively. (a) yearly atmospheric bulk chloride deposition (A_P, g m^{-2} year^{-1}), chloride content of local recharge water (C_R, mg L^{-1}) used to estimate recharge; and groundwater chloride content from large springs and deep wells (C_R*, mg L^{-1}) used to calibrate recharge (Alcalá et al., 2007, 2011); the functions for C_R and C_R* that best fit experimental data are superimposed. (b) Elevation and yearly recharge rate (R, mm year^{-1}) deduced from A_P-C_R data and A_P-C_R* data along the slope. Regional geology at 1:100,000 scale: 1 Paleozoic schist (N); 2 Paleozoic schist (A); 3 Triassic marble (N); 4 Permian to-Triassic phyllite (A); 5 Triassic limestone and dolomite (A); 6 Triassic limestone (A); 7 Upper Tortonian to Pliocene sediments; 8 Quaternary sediments. N Nevado-Filabride and A Alpujarride tectonic complexes (Internal Betic Zone).

years. C_R values of large springs and deep wells (C_R*), which integrate the *R*-values (and their C_R values) produced at different altitudes, were used to calibrate estimates (Fig. 3a). Average recharge rates vary from less than 20 mm year^{-1} on the coast to around 250 mm year^{-1} at the summit.

In Sierra de Gádor, as in other mountainous carbonated massifs in SE Spain, the mix of infiltration fluxes yielded at different altitudes is important. Using C_R* data, average recharge is overestimated by 30% on average, and so correction is needed (Fig. 3b). C_R data of shallow, perched aquifers provide accurate recharge estimates, neglecting the effect of this mixing infiltration on the regional water table (Alcalá et al., 2011). The recharge function can be regionalized within a GIS using geostatistical tools (Alcalá and Custodio, 2008a).

3.3. Using numerical-modeling techniques to estimate actual recharge

Numerical modeling techniques have been widely used in the region. According to how the spatial heterogeneity of input variables and parameters are introduced and spatially managed, models can be classified as lumped or spatially distributed. Examples of lumped models applied in SE Spain are VENTOS (Bellot et al., 2001), BALAN (Samper, 1998), ERAS (Murillo and De la Orden, 1996) and TRIDEP (Padilla and Pulido-Bosch, 2008). Three-dimensional distributed models based on numerical codes, such as MODFLOW (McDonald and Harbaugh, 1988) or SEAWAT (Guo and Langevin, 2011), have been used in inland and coastal detrital aquifers (Calvache and Pulido-Bosch, 1994).

The lumped parameter model ERAS has been one of the most widely-used water table fluctuation models for estimating actual recharge rates (Murillo and Roncero, 2005; Aguilera and Murillo, 2009). The easy access to groundwater level data and the simplicity of the numerical code allow its application in many small overexploited carbonate aquifers in SE Spain with a pronounced negative water table tendency. The ERAS model computes the volume of actual recharge, *R*, at the water table for a given time interval *i* (*op. cit.*):

$$R_i = M\cdot\left(P_i - T_i^{\beta}\right)^N\cdot A \tag{4}$$

where P_i is the rainfall over the period in mm, T_i is the average air temperature in °C, and *A* is the aquifer's permeable outcrop in m^2. β is a dimensionless calibration parameter for converting temperature into potential evapotranspiration. It ranges from 1.3 for cold zones to 1.6 for warmer zones (MMA, 2000). *M* and *N* parameters, which must be previously calibrated using data on the water table dynamics, determine the fraction of effective rainfall (i.e., $P_i - T_i^{\beta}$) expected to reach the water table.

The variation of stored water in the aquifer can be computed as:

$$\Delta V_i = \Delta h_i\cdot A\cdot S \tag{5}$$

where Δh_i is the observed water table change (m), and *S* is the aquifer storage coefficient. Because ΔV_i derives from the balance between actual recharge R_i (inflows) and the pumping rate B_i (outflows), Δh_i can be expressed as:

$$\Delta h_i = \frac{M\left(P_i - T_i^{\beta}\right)^N\cdot A - B_i}{S\cdot A} \tag{6}$$

Finally, *M* and *N* are fitted for the balance period using observed Δh_i values against simulated values computed from P_i, T_i and B_i data.

Results from the ERAS model application in different carbonate aquifers in Murcia and Alicante provinces (Fig. 1) are shown in Table 1. Mean annual recharge rates relative to precipitation rates range between 0.04 and 0.47. Differences in recharge are explained by local differences in soil properties and vegetation cover, geological heterogeneities, degree of karstification and fracturation. Using the ERAS modeling approach, Martínez-Santos and Andreu (2010) confirmed a general pattern of low recharge rates in small carbonated aquifers of SE Spain, with low inertia to rainfall events and where periods without significant recharge can last more than one year (Fig. 4). Despite the particular hydrogeological functioning of these small aquifers, they are extremely sensitive to intensive pumping. This is the case of the Ventós aquifer, where an extraction rate of 0.3 Mm^3 year^{-1} (9.5% mean annual precipitation) over a period of 30 years has caused a drop in the water table of 80 m.

3.4. Isotopic studies to identify sources and altitude of recharge

Numerous stable isotopic studies have been performed to evaluate the sources of recharge in SE Spain (e.g., Cruz-Sanjulián et al., 1992; Vallejos et al., 1997; Frot et al., 2007; Alcalá et al., 2007). Evaporation during the generation and transport of water vapour from the Ocean determines the signature and the fractioning between ^{18}O and ^{2}H in the water molecules (Craig, 1961). When air masses are orographically uplifted, they cool and precipitate preferentially the heavier isotopes. This property is useful for calculating the relative contribution of groundwater recharge produced at different altitudes.

The understanding of the sources can be improved using the deuterium excess (*d*) as a conservative tracer (Craig, 1961):

Table 1
Actual recharge rates estimated using the ERAS model in several aquifers of SE Spain. P and R are average values for observed precipitation and estimated recharge in the simulation period (mm yr^{-1}).

Water body (ID, Fig. 1)	Area (km^2)	Altitude range (Min–Max)	Main lithology	Age	Simulation period	Rainfall-type period	P	R	Calibration			Reference
									Period	M	N	
Ventós (3)	7	380–900	L	C	1997–2000	Dry	242	7	1997–2000	0.01	1.22	Andreu et al. (2001)
					1999–2007		272	13	1999–2007	0.06	1.22	Martínez-Santos and Andreu (2010)
Peñarrubia (4)	41.5	500–1042	L, D	J–E	1960–1999	Average	372	114	1988–1998	0.88	4.35	Murillo and Roncero (2005)
					1900–2000		446	163	1988–1999	0.86	0.96	Aguilera and Murillo (2009)
Serral-Salinas (6)	198	500–1240	L, D	C	1960–1999	Average	372	49	1989	1.87	0.21	Corral et al. (2004)
					1900–2000		446	18	1989	0.12	0.90	Aguilera and Murillo (2009)
Cabeçó d'Or (4)	15	400–1208	L	J	1977–1987	Average	400	68	1977–1987	1.55	0.90	Murillo and De la Orden (1996)
Solana (7)	118	500–990	L, D	C	1989–1999	Dry	333	76	1994–1997	0.90	0.89	Murillo et al. (2004)
					1900–2000	Average	446	208	1994–1997	0.93	1.01	Aguilera and Murillo (2009)
Jumilla-Villena (8)	320	500–700	L, D	C	1900–2000	Average	446	56	1998–2002	0.20	1.20	Aguilera and Murillo (2009)

Main lithology: L = limestone; D = dolomite; Age: C = Cretaceuos; J = Jurassic; E = Eocene

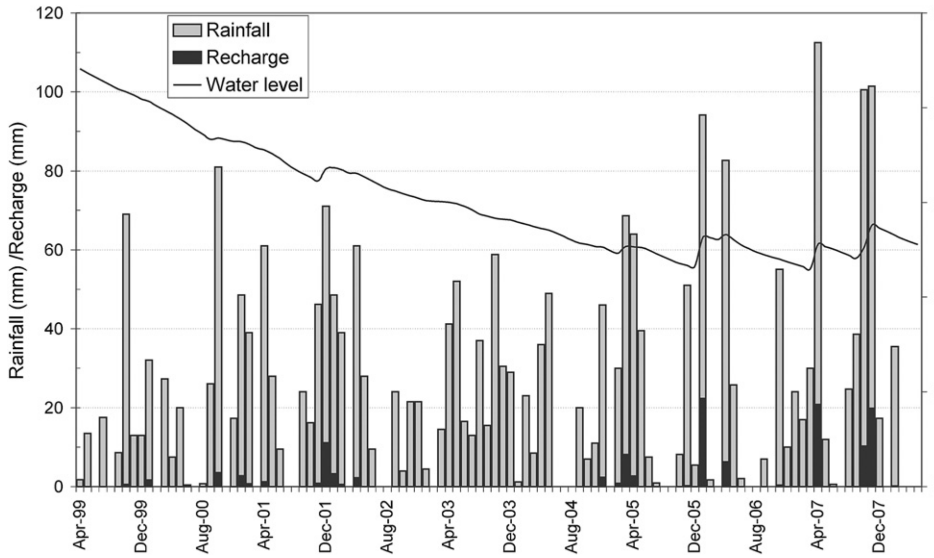

Fig. 4. Actual recharge estimation by ERAS model in the Ventós aquifer (GWB number 3 in Fig. 1) for the 1999–2008 simulation period (modified from Martínez-Santos and Andreu, 2010).

$$d = \delta^2\mathrm{H} - 8\delta^{18}\mathrm{O} \tag{7}$$

where δ represents the isotopic concentration relative to the standard VSMOW (Vienna Standard Mean Ocean Water). The d-value changes depend on the relative air humidity and temperature during the evaporation process that produces the water vapour of the clouds. The SE Spain is a mixing zone where precipitation originates from water vapour from the Atlantic Ocean and the Mediterranean Sea (Frot et al., 2007).

The study of daily synoptic situations shows that rainfall generation at low altitude is preferentially dominated by air masses entering from the Atlantic Ocean, providing average d-values of around 10‰ (Alcalá et al., 2007; Frot et al., 2007). The influence of air masses entering from the Mediterranean basin increases progressively to give d-values of more than 15‰ (up to 20‰) on the mountain summits (Cruz-Sanjulián et al., 1992; Vallejos et al., 1997). The variation of d-value found in Sierra de Gádor is similar to that recorded in other mountainous areas of SE Spain (Cruz-Sanjulián et al., 1992).

In a δ^{18}O–δ^2H plot, the isotopic δ^{18}O and δ^2H signatures of rainfall-amount-weighted samples collected from 2004 to 2007 at 12 rainfall stations situated between 38 and 1939 m a.s.l. in Sierra de Gádor Mountains plot between the Global Meteoric Water Line and the Western Mediterranean Meteoric Water Line (Fig. 5 a). The local meteoric water line shows a slope of 7 and $R^2 = 0.95$. These ^{18}O and ^{2}H signatures range from −6‰ to −45‰ along the coast to −10‰ and −70‰ on the mountain summits. This spatial variation of meteoric waters controls the ^{18}O signature of groundwater. Groundwater flow integrates recharge infiltrating at different altitudes (Fig. 5 b). The altitudinal gradient of ^{18}O for meteoric waters is −0.25‰ 100 m^{-1} (Cruz-Sanjulián et al., 1992; Vallejos et al., 1997; Alcalá et al., 2007). This gradient was used to trace the main elevation range for aquifer recharge. Assuming a linear mixing model of recharge produced at different elevations, Alcalá et al. (2007) calculated an average altitudinal gradient of ^{18}O in groundwater of −0.09‰ 100 m^{-1}. The main area for recharge appears to be between 1200 and 1700 m a.s.l. (Vallejos et al., 1997), induced by the highest rainfall rates and the greater karstification at this altitude.

4. Discussion

Stimulated by the entry into force of the EU-Water Framework Directive, a growing number of studies have been carried out to characterize aquifer recharge in groundwater bodies in SE Spain. Specific examples outlined in this article illustrate how different

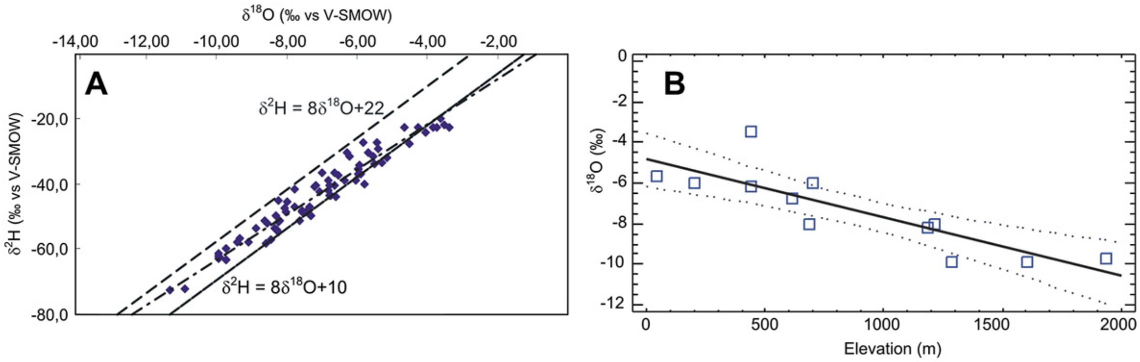

Fig. 5. (A) Oxygen-18 vs. deuterium plot from Sierra de Gádor precipitation samples (Global Meteoric Water Line: solid line, Mediterranean Meteoric Water Line: broken line, Linear regression analysis: dotted line). (B) Plot of oxygen-18 vs. elevation (linear regression analysis: solid line, Confidence level 95%: broken line).

methodologies were used to investigate the spatiotemporal pattern of potential and actual recharge rates in carbonated massifs. These formations are the most important groundwater reservoirs in the region.

A wide number of techniques with different degree of complexity, input data required and possibility for validating results have been used to quantify potential and actual recharge in most heterogeneous carbonated massifs in SE Spain. For a similar rainfall period, the methods addressing the soil, the unsaturated zone and the saturated zone provided different magnitude of recharge. It should be noted that potential and actual recharge observations involve different timing and hydrological meaning, where potential usually exceeds actual recharge due to losses expected to be produced in the vadose zone.

The soil water balance is the most widely-used technique to quantify potential recharge rates below the root zone. Potential recharge rates yielded by both physical and tracer techniques (i.e., the CMB method) in mountainous carbonated areas of the region, such as the Sierra de Gádor Mountains, are $40 \pm 15\%$ (average $\pm$ 1 s.d.) of the mean annual precipitation, with spurious values ranging from 1% to 75% (Contreras et al., 2008; Cantón et al., 2010). These figures suggest that diffuse recharge in carbonated mountainous areas, widely developed in Mediterranean environments, may represent a significant proportion of the total potential recharge in wet and average rainfall years but a negligible proportion in dry periods (Alcalá et al., 2011; Martínez-Santos and Andreu, 2010). The low surface runoff rates imposed by the medium-high karstification degree of these systems and the relatively low evapotranspiration rates driven by the low vegetation cover mean that concentrated recharge plays an important role in the total water balance, especially during those dry periods in which short and intense rainfall events are common (Martín-Rosales et al., 2007). Large runoff events tend to infiltrate at footslopes of carbonated massifs in Quaternary formations (Martín-Rosales et al., 2007), thus increasing the uncertainty of potential recharge estimates if runoff was assumed previously as aquifer recharge.

The ERAS code, a lumped model based on the analysis of water table dynamics in small carbonated aquifers, provides actual recharge estimates from 5% to 45% of annual precipitation. The estimates have already discounted the fraction of runoff and other potential losses produced in the vadose zone during the infiltration process. The observation of water level changes as the response to recharge events is a prerequisite for the correct model application. However, in dry periods this is not possible. This means that a significant amount of small recharge events may go unnoticed for long-term actual recharge evaluations. Since estimates of actual recharge correspond to a fraction of the effective rainfall, these methods have the advantage that they do not require the movement of water to be known in either the soil or the unsaturated zone. However, this advantage can limit the calibration with alternative methods because actual recharge variability becomes smoother as the thickness of the unsaturated zone increases.

Regardless of the method used, the divergence of potential and actual recharge can have transitory and seasonal causes. The difference between potential and actual recharge is shown to be less than 5% in homogeneous, level areas under a semiarid climate where the runoff rate is low to moderate (Lerner et al., 1990; Scanlon et al., 2002). The difference diminishes when runoff is incorporated into the water balance, when the potential groundwater abstraction from perched aquifer levels is known, or when the diffuse transfer of recharge in transit into other groundwater bodies is known. On the other hand, the difference between potential and actual recharge can reach 30% in mountainous areas that have an abrupt relief, where geological heterogeneity is large and where permeability is moderate (Simmers et al., 1997; Custodio et al., 1997). In mountainous carbonated massifs, where the vadose zone may be as much as 1000 m thick, these influencing factors can occur together leading to the discharge of part of the potential recharge in transit through small springs, from which the water flows towards rivers, the sea or other groundwater bodies.

In addition to these seasonal causes, there are transitory ones, such as the negative trend of the phreatic level when the aquifer is being intensively pumped. In the southeast of Spain, as in other semiarid areas, a drop in piezometric level caused by pumping makes longer the transit time of the recharge water through the vadose zone, and this can even limit the comparison between inflow from precipitation and the associated rise in phreatic level. This divergence can be significant even in small aquifers if the permeability is moderate and the period of observation is long.

The common limitations for achieving a precise and accurate estimate of the potential and actual recharge in mountainous carbonated aquifers may, nevertheless, be used to obtain additional information about the hydrological operation of the aquifer (such as transit time or recharge mechanisms). Where the aquifer medium is well known, the differences can be interpreted to assess possible lateral transfers between aquifers or the role that is played by runoff – which is usually small in comparison to the recharge (1:50–100 at high altitude and 1:25–50 in the lowlands) – as mechanisms of recharge generation at different altitudes or in preferential locations. The use of stable isotopes is a proven tool for validating hypotheses of mechanisms of recharge and discharge and of the flow systems within the aquifer.

Taking into account the divergence between potential and actual recharge estimates in carbonated aquifers, the assessment of spatial patterns of recharge constitutes another great challenge (Entekhabi and Moghaddam, 2007), which has been tackled in SE Spain using spatially-distributed modeling, chemical and isotopic techniques, and other local empirical methods (Andreo et al., 2008). The high spatial heterogeneity in land cover and surface processes (e.g. evapotranspiration and surface runoff) that are typical of semiarid regions could be incorporated into spatially-distributed models with data provided by remote sensing. Satellite data have proved to be able to define land units with similar hydrological response (Bellot et al., 2001; Frot and van Wesemael, 2009) and to quantify actual evapotranspiration rates using ecological modeling based on the regional analysis of the anomalies in a spectral vegetation index (Contreras et al., 2008). Characterization of the conservative chemicals and isotopic signatures of rainfall, soil moisture and groundwater has contributed to the understanding of the mechanisms of recharge generation in the region (Cruz-Sanjulián et al., 1992; Vallejos et al., 1997; Frot et al., 2007; Alcalá et al., 2007, 2011). The effect of distance from the coast and altitude in determining the atmospheric chloride deposition and the impoverishment of heavy isotopes (^{18}O and ^{2}H) in rainwater are steady properties that have been shown to establish regional patterns of recharge generation.

The sensitivity of different models to changes in their parameters has been addressed by several studies (Contreras et al., 2008; Aguilera and Murillo, 2009). However, uncertainty analyses, even an appraisal of recharge natural variability, are still scarce. For example, research underway stresses the importance of correct evaluation of surface runoff in reducing the error in recharge estimation to 5–15% in carbonated massifs (Alcalá et al., 2011). Given the scarcity of runoff measurements, several recharge assessments have simulated it using empirical approaches based on the soil number curve procedure (Martín-Rosales et al., 2007). A better knowledge of the hydrological functioning of the headwater catchments of the region through intensive monitoring of rainfall, runoff, spring discharge and actual evapotranspiration is sorely needed.

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