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ORIGINAL ARTICLE

Diffuse and concentrated recharge evaluation using physical and tracer techniques: results from a semiarid carbonate massif aquifer in southeastern Spain

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Abstract In the high-permeability, semiarid carbonate aquifer in the Sierra de Gádor Mountains (southeastern Spain), some local springs draining shallow perched aquifers were of assistance in assessing applicability of the atmospheric chloride mass balance (CMB) for quantifying total yearly recharge (R_T) by rainfall. Two contrasting hydrological years (October through September) were selected to evaluate the influence of climate on recharge: the average rainfall year 2003–2004, and the unusually dry 2004–2005. Results at small catchment scale were calibrated with estimated daily stand-scale R_T obtained by means of a soil water balance (SWB) of rainfall, using the actual evapotranspiration measured by the eddy covariance (EC) technique. R_T ranged from 0.35 to 0.40 of rainfall in the year, with less than a 5% difference between the CMB and SWB methods in 2003–2004. R_T varied from less than 0.05 of rainfall at mid-elevation to 0.20 at high elevation in 2004–2005, with a similar difference between the methods. Diffuse recharge (R_D) by rainfall was quantified from daily soil water content field data to split R_T into R_D and the expected concentrated recharge (R_C) at catchment scale in both hydrological years. R_D was 0.16 of rainfall in 2003–2004 and 0.01 in 2004–2005. Under common 1- to 3-day rainfall events, the hydraulic effect of R_D is delayed from

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1 day to 1 week, while R_C is not delayed. This study shows that the CMB method is a suitable tool for yearly values complementing and extending the more widely used SWB in ungauged mountain carbonate aquifers with negligible runoff. The slight difference between R_T rates at small catchment and stand scales enables results to be validated and provides new estimates to parameterize R_T with rainfall depth after checking the weight of diffuse and concentrated mechanisms on R_T during moderate rainfall periods and episodes of marked climatic aridity.

Keywords Recharge · Diffuse · Concentrated · Mountain carbonate areas · Semiarid climate · SE Spain

Introduction

Aquifer recharge is the fraction of infiltrating precipitation and surface water that enters an underlying phreatic aquifer through the water table some time after the infiltration event. The remaining fraction of infiltration is transpired by plants, evaporated from the soil or returned to the surface as interflow or discharge of shallow ephemeral perched aquifers (Custodio et al. 1997). Recharge refers to water table aquifers and from these it may be transferred to deeper aquifers, vertically through aquitards or by lateral groundwater flow. This total recharge (R_T), which penetrates the water table and the capillary fringe, should be differentiated from net recharge, which is what remains in the water table aquifer after discounting uptake by phreatophytes (De Vries and Simmers 2002). Net recharge adds to aquifer storage and moves toward the aquifer system discharge points and areas.

Under normal circumstances in temperate and semiarid regions, most aquifer recharge comes from rainfall infiltration. However, in arid and dry piedmont areas, recharge from permanent or ephemeral streams may be important, more so the more arid the area is (Wood et al. 1997; Sorman et al. 1997). This may also be relevant in mountainous areas on the fringes of snowmelt (Gee and Hillel 1988; Simmers et al. 1997).

Rainfall infiltration in porous media produces diffuse recharge (R_D). R_D makes up the majority of R_T in well-developed soils in flat areas in temperate to humid climates (Maréchal et al. 2009), but may be less than 0.5 R_T during average rainfall years and negligible during dry periods in semiarid mountainous regions (Keese et al. 2005). Aquifer recharge may also be considered diffuse when infiltration is through profuse soil cracks and discontinuities in densely fractured rocks (Simmers et al. 1997). In such cases, part of infiltration water may avoid pedologic soil evapotranspiration processes. Infiltration from streams, major fractures, sinkholes, etc., is concentrated recharge (R_C) affecting a small fraction of the territory and producing local hydrological and hydrogeochemical responses in groundwater storage and quality. R_C makes up the majority of R_T in well-developed karstic systems (Andreo et al. 2008; Li et al. 2008) or in fissured and bare bedrock areas in arid regions (Wood et al. 1997; Simmers et al. 1997).

In most large semiarid carbonate mountainous regions, and especially in well-developed karstic systems in temperate regions, conditions are suitable for variable contributions to R_T by both true diffuse and concentrated mechanisms, depending on variations in climate, land use, soil and vegetation cover, slope, lithology, fracturation, etc., in the territory (Lerner et al. 1990; Wood et al. 1997; Simmers et al. 1997; De Vries and Simmers 2002). Although the separation is not clear, on the basis of the existence of a significant fraction of R_C in R_T, it may be said that R_T is less affected by evapotranspiration and negligibly by surface runoff (Custodio et al. 1997). In these areas, seasonal variation in climate, along with elevation, combine with long-term global climate cycles to increase precipitation with elevation. R_T may increase from less than 0.1 of annual rainfall at lower altitudes to around 0.5 at higher altitudes, involving a variable proportion of both true R_D and R_C recharge components (Gee and Hillel 1988; Lerner et al. 1990; Contreras et al. 2008).

A better understanding of the mechanisms that control the generation of recharge to aquifers is required to implement sustainable water management polices (Kovalevskii 2007). This is a challenge for future research in applied hydrology (De Vries and Simmers 2002), especially when these components fluctuate widely in time and space in semiarid regions such as southern Spain where groundwater is the main water resource.

Recharge evaluation techniques vary from those focusing on local rainfall events to those yielding long-term areal values. The soil water balance (SWB) method is the most widely used technique to estimate R_T from arid to humid regions at different spatiotemporal scales. Its complexity and accuracy depend on the number of hydrological and environmental variables involved (Lerner et al. 1990; Simmers et al. 1997; Scanlon et al. 2006). R_T is usually found as the residual term of other dominant terms, and consequently the result may be highly uncertain and occasionally biased, especially in dry climates (Wood et al. 1997; Ross et al. 2001; Keese et al. 2005). It is therefore highly advisable to use alternative methods to compare long-term estimates (De Vries and Simmers 2002; Scanlon et al. 2006). In semiarid regions, aquifers usually have deep water tables and only recurrent dry or long wet periods affect the net value of R_T at the water table. This means that methods applied in the saturated zone, such as hydrodynamic methods (e.g., water table fluctuation, equal volume spring flow, etc.) or those based on Darcy's Law, may be limited for estimating short-term R_T, while historical tracers (radioisotopes) provide accurate long-term R_T averages, smoothing out natural variability by attenuating extreme climatic events in the transit through the unsaturated zone (Lerner et al. 1990; Custodio et al. 1997; Simmers et al. 1997).

In high-permeability mountainous carbonate regions, intermediate groundwater discharges through local springs draining shallow perched aquifers are good places to study in transit (percolating) R_T at the top of the regional unsaturated (vadose) zone. At this spatial scale, the climatic events influencing long-term precipitation can be recorded as smoothed out over time variations in R_T. The atmospheric chloride mass balance (CMB) method is a well-known and widely used technique for estimating low R_T rates in flat continental sedimentary areas (Wood and Sanford 1995; Custodio et al. 1997; Scanlon et al. 2006). The application of this technique to coastal mountainous regions has to take into account the high spatial gradients in atmospheric chloride deposition and the possibility that a water sample is a mixture of recharge water produced in different parts of the territory and different elevations, increasing the uncertainty in R_T estimation (Custodio et al. 1997; Alcalá et al. 2007; Custodio 2009a). The recharge chloride content measured at the top of the water table includes unknown proportions from true R_D and recharge through frequent soil cracks and densely distributed rock fissures, which may have similar saline evapoconcentration effects (Wood et al. 1997). Evaporation is not involved in formulations, which helps to reduce the uncertainty in R_T estimation.

R_T and R_D can be quantified accurately at stand scale at representative sites by using specific methodologies based on daily variation in soil water content (Simmers et al. 1997; Scanlon et al. 2006; Eliers et al. 2007; Maréchal et al. 2009) to compare estimated R_T and to assess the expected R_C and R_D fractions at small catchment scale. Accurate daily R_T and R_D estimation at stand scale involves complex instrumentation that is only available at experimental or especially monitored sites. This means that accurate R_T estimates are limited to a few places, leaving no possibility of use for regional results, which is the case in most mountainous areas where evapotranspiration and recharge vary widely with elevation. The CMB method is a complement to the most widely used SWB methods, in order to regionalize R_T estimates.

The purpose of this study is (1) to assess the applicability of the CMB method for estimating seasonal R_T in transit at small catchment scale to parameterize recharge in semiarid mountain carbonate aquifers without data, and (2) to evaluate the split of R_T in transit into R_D and R_C at that spatial scale.

To meet these goals, (1) R_T is evaluated in two contrasting hydrological years, the average rainfall year 2003–2004 and the unusually dry 2004–2005 to find out how the climate difference affects CMB estimates; (2) seasonal R_T in transit is calibrated at catchment scale with accurate daily stand-scale R_T estimates using an SWB method for the same period and elevation range; (3) daily stand-scale R_T and R_D is quantified to evaluate the expected split of R_T in transit into R_D and R_C at small catchment scale in these two contrasting years, after checking that deviation between seasonal and daily R_T estimates becomes negligible.

This research is part of a larger study designed to identify mechanisms and magnitude of recharge by rainfall in ungauged carbonate aquifers.

Methods and data acquisition

Regional setting and study sites

The Sierra de Gádor Mountains (peak altitude 2,246 m a.s.l.) is a 670 km^2 Mediterranean semiarid-to-subhumid carbonate range. It is the main recharge area for the deep aquifers in the Campo de Dalías. The Campo de Dalías is a 360-km^2 semiarid coastal plain that is intensively exploited for groundwater to irrigate 260 km^2 of greenhouses (Pulido-Bosch et al. 2000). They are placed in southeast Spain, between 36°40′N–37°01′N and 2°30′W–2°59′W (Fig. 1).

The Sierra de Gádor Mountains consist of a thick series of highly permeable Triassic limestone and dolomites (Fig. 2a), underlain by low-permeable Permian to Triassic metapelites belonging to the Gádor and Felix Units of the Alpujárride tectonic Complex, Internal Zone of the Betic Range (Martin-Rojas et al. 2009). This unconfined Triassic carbonate aquifers continue under the Campo de Dalías coastal plain overlain by Miocene to Pliocene calcarenites and marls and Quaternary colluvials (Domínguez 2000; Marín-Lechado et al. 2005).

Precipitation in the Sierra de Gádor Mountains comes in similar proportion from the Atlantic Ocean frontal atmospheric depressions and convective storms from the Mediterranean Sea basin. Daily synoptic data at the mean sea level can be found in the European Centre for Medium-Range Weather Forecasts (ECMWF: http://data-portal.ecmwf.int/data/d/era40_daily/). The semiarid climate modulates high intra- and inter-annual variability in yearly precipitation. Average values range from 215 mm year^{-1} in El Ejido to 650 mm year^{-1} at the summit of the Sierra de Gádor with maxima in autumn and minima in summer (Summer et al. 2000; Lázaro et al. 2001). Study of data from a representative weather station, La Zarba (36°55′00″N, 2°38′21″W, 1,219 m a.s.l.; Fig. 1), which has a 30-year precipitation record, indicates that yearly precipitation varies from less than 200 mm year^{-1} for extremely

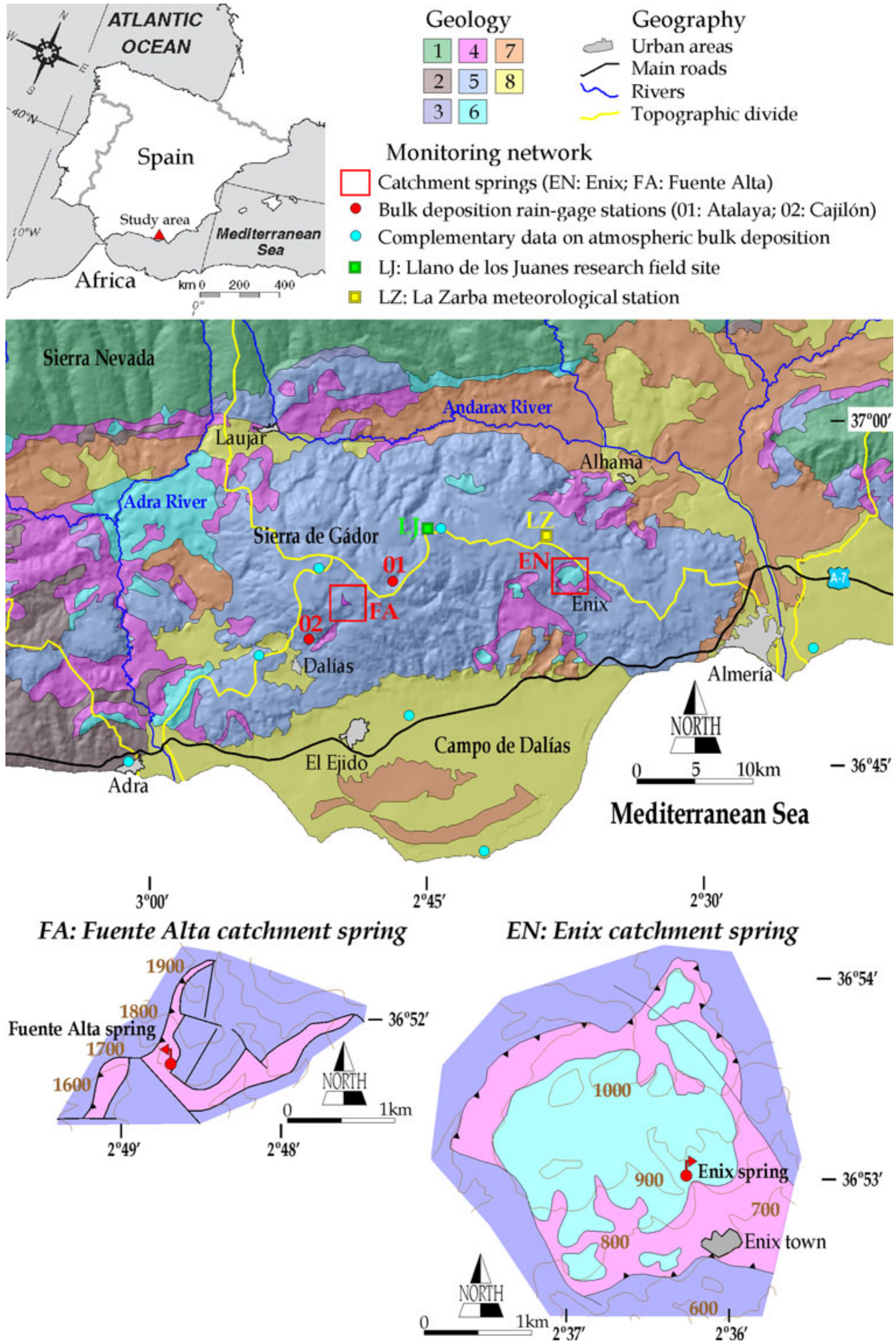

Fig. 1 Location of the Sierra de Gádor Mountains and sites cited in the text on the map compiled from a DEM (50 m resolution). Regional geology at 1:100,000 scale is from Martin-Rojas et al. (2009) *1* Paleozoic schists (N); *2* Paleozoic schists (A); *3* Triassic marbles (N); *4* Permian to Triassic phyllites (A); *5* Triassic limestone and dolomites (A); *6* Triassic limestone (A); *7* Upper Tortonian to Pliocene sediments; *8* Quaternary sediments. *N* Nevado-Filabride and *A* Alpujarride tectonic complexes (internal zone of the Betic Range)

dry rainfall years to more than 900 mm year^{-1} for extremely wet rainfall years, with a yearly average of 463 mm year^{-1} and a coefficient of variation of yearly values of 0.38.

The average yearly temperature is around 18°C at the coastal plain and 9°C at the summit, contributing to evaporation rates from around 0.5 of yearly precipitation in the summit areas to about 0.85 in the lower areas (Contreras et al. 2008).

Recharge comes from mixed infiltration of rainfall at different altitudes in the Sierra de Gádor Mountains, varying from less than 40 mm year^{-1} at the coast to more than 250 mm year^{-1} at the higher areas (Domínguez 2000; Alcalá et al. 2007; Contreras et al. 2008). Groundwater

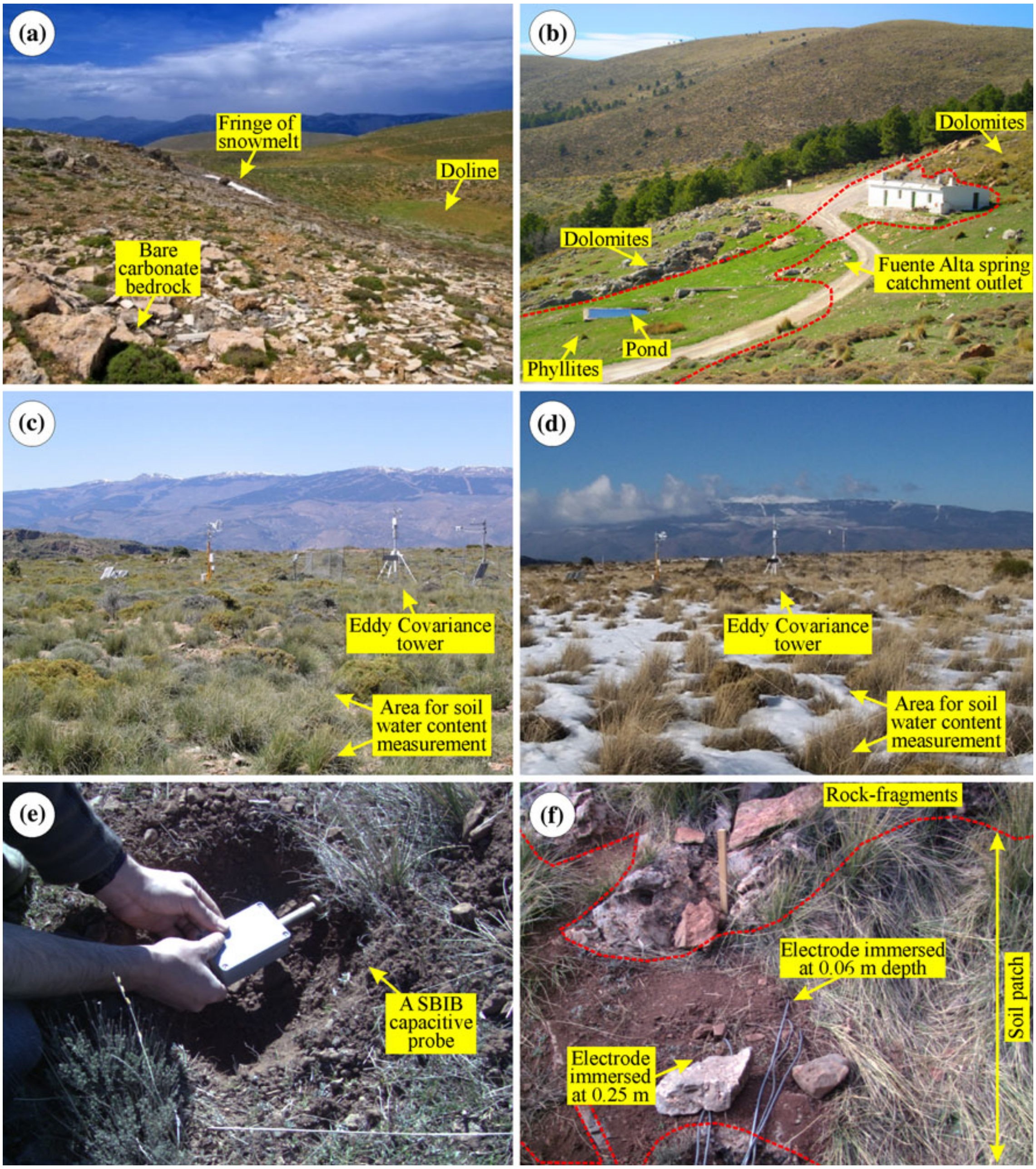

Fig. 2 **a** Carbonate landscape in Sierra de Gádor Mountains summit. **b** Panoramic view of Fuente Alta Spring catchment outlet. **c** Instrumentation and appearance of vegetation and high stoniness in the Llano de los Juanes site in spring and **d** in winter. **e** Soil water content measurement by using a self-balanced impedance bridge (SBIB) capacitive probe at the Llano de Los Juanes field site and **f** by immersing temporarily two electrodes in the soil at 0.06 and 0.25 m depth

pumping from the deep Triassic carbonate aquifers in the Campo de Dalías is currently the main aquifer water discharge. Intensive groundwater exploitation of 140 Mm^3 (million m^3) per year (around 250 mm $year^{-1}$), to irrigate the 260 km^2 of greenhouses (70% of total surface) and supply 250,000 inhabitants and tourist activities on the coastal plain, is more than twice the estimated average weighed recharge by rainfall ($\sim$150 mm $year^{-1}$), producing a regional water table depletion, diminished water quality, marine intrusion and mobilization of marine brines and diffuse agricultural pollutants (Pulido-Bosch et al. 2000).

Regional hydrogeological surveys and analysis of the stable isotopic signature of rainfall and groundwater show that the most suitable range for recharge generation is from 1,000 m a.s.l. up to the summit (Cruz-Sanjulián et al. 1992;

Vallejos et al. 1997; Domínguez 2000; Vandenschrick et al. 2002; Alcalá et al. 2007; Contreras et al. 2008).

Two small representative catchment springs draining shallow perched aquifers (Fuente Alta and Enix) at the mid-to-high southern slope of the Sierra de Gádor Mountains (SE Spain) were selected to evaluate seasonal R_T using the CMB method in 2003–2004 and 2004–2005 (Figs. 1, 2b; Table 1). In the nearby Llano de los Juanes research site (Figs. 1, 2c, d; Table 1), daily R_T was quantified by an SWB method and daily R_D was estimated from soil water content field data to evaluate both R_D and R_C fractions in seasonal catchment-scale R_T estimates.

The Fuente Alta and Enix local springs are located at the upper and the lower boundaries of the main recharge elevation. The Llano de los Juanes is a representative area for estimating stand-scale R_T and R_D in the same range of elevations. The geological structure and lithology, soil properties (e.g., thickness, types) and vegetation cover are similar at the Fuente Alta and Enix springs and Llano de los Juanes, which allows recharge mechanisms and rates at stand and small catchment scales to be compared.

Both the Fuente Alta and Enix local springs drain shallow perched carbonate aquifers on a thin, low-permeable layer of metapelites intersected by the local surface without significant deep percolation through the impervious base (Fig. 2b). Discharge represents the R_T in transit beyond the root zone in these small catchments, characterized by their limited capacity to yield runoff (Frot et al. 2008). From a hydrogeological point of view, R_T is the total recharge rate at a given site that is expected to reach the regional water table in the future.

Llano de los Juanes is an isolated, 2 km^2 flat summit area of structural origin that has been used as a research site since September 2003 to assess in detail the terms involved in the water balance (Fig. 2c, d). Soil at this site has been classified as a Lithic Haploxeroll–Lithic Ruptic Argixeroll complex (Oyonarte et al. 1998). Soil is thin (average 35 cm) and discontinuous over limestone bedrock, with scattered rock fragment cover and throughout the soil profile (Fig. 2e, f). This soil is a clayey loam with 40–59% silt and 21–68% clay, with alluvial clay deposits in the subsurface horizon. Organic matter content is relatively high, ranging from 1.3 to 7.3%. The mean bulk density is 1.1 g cm^{-3}, and the unsaturated hydraulic conductivity averages 1.5–1.6 mm h^{-1} at 120 mm water tension and 12–194 mm h^{-1} at 30 mm water tension (Li et al. 2008; Cantón et al. 2010). The soil surface is covered by a mosaic of patchy dwarf perennial shrubs and grasses, rock outcrops and bare soil with patches of rock fragments interspersed with vegetation. *Genista* predominates among woody shrubs and *Festuca* in the herbaceous stratum (Fig. 2c–f).

Estimating total, diffuse and concentrated recharge at stand scale

The specific hydrological boundary conditions of Llano de los Juanes are of assistance in studying detailed recharge mechanisms and rates: (1) summit area without inflow runoff from other areas; (2) flat area with no stream beds in which runoff (overland and interflow) exists only over short distances (up to 20 m) and produces concentrated recharge in cracks, joints, fissures, etc. (Li et al. 2008; Frot et al. 2008); (3) maxima precipitation and soil water content in late autumn–early winter and minima in late summer–early autumn (Lázaro et al. 2001; Cantón et al. 2010). Under steady-state conditions, for a sufficiently long period such as 1 hydrological year (October through September), change in initial and final soil moisture is negligible and the water balance in the soil can be expressed as:

$$P = E + R_D + R_C \quad (1)$$

where P measured rainfall in the site; E actual evapotranspiration; R_D true diffuse recharge produced in a porous media percolating out of the soil root zone in excess of soil moisture water-holding capacity after discounting E; R_C a combination of mechanisms from quasi-diffuse recharge in profuse soil cracks and discontinuities to true concentrated recharge bypassing the soil root zone through preferred pathways (e.g., macropores) and discrete fractures, sinkholes, etc., with a relatively high infiltration capacity, after discounting the part of E that affects the process. Terms are expressed as depth per unit of surface, i.e., mm, and they refer to the

Table 1 Fuente Alta and Enix catchment springs and Llano de los Juanes site description

Catchment/site	Coordinates	Elevation (m a.s.l.)	A (m^2)	H (m)
Fuente Alta (spring)	36°52′02″N 2°48′36″W	1,735	22 10^4	1,735–1,805
Enix (spring)	36°52′58″N 2°36′11″W	825	46 10^4	825–995
Llano de los Juanes (plain)	36°55′56″N 2°44′55″W	1,600	15 10^3	1,600

A is the surface receiving total recharge susceptible to be discharged through local springs; *H* is the range of elevation from the upper boundary to the discharge point of the catchments balance period, here 1 day long. The sum of R_D and R_C represents the total recharge (R_T). Thus, Eq. 1 becomes:

$$P = E + R_T. \quad (2)$$

Rainfall amount and intensity were recorded daily by an automatic 0.2-mm resolution tipping-bucket rain gauge (model 785M®, Davis Instruments Corp., Hayward, USA) from October 2003 to September 2005.

E was quantified daily by the eddy covariance (EC) technique (Anderson et al. 1984; Verma et al. 1986) in Table 2. The EC system includes a three-dimensional sonic anemometer CSAT3® [Campbell Scientific Inc. (CSI), USA] for measuring the three wind speed components and a krypton hygrometer KH20® (CSI, USA) for measuring water vapor concentration (Fig. 2c, d). Air temperature and humidity were measured by a thermohygrometer HMP 35C® (CSI, USA). Data were acquired and stored by a datalogger CR23X® (CSI, USA). Mean values, variances and co-variances of 10 Hz data were calculated and stored every 30 min. Data correction, post-processing and gap filling is described in Kowalski et al. (1997) and Serrano-Ortiz et al. (2009). E is a representative value of the ecosystem that incorporates all soil, vegetation and lithology heterogeneity.

The principle of R_T estimation in homogeneous soils by the SWB method is that the soil becomes free draining when the soil moisture content (θ) reaches a limiting value called the field capacity (θ_{FC}). θ is the volumetric percentage of water or depth of water if the soil is considered a bucket taking its average thickness into account. To quantify R_T in 1-day time steps in Sierra de Gádor Mountains, daily soil moisture conditions throughout the year must be simulated (Rushton et al. 2006). R_T is found from daily P and E. The soil water content is calculated at each time step from the previous value as:

$$R_T = \theta_D \,(\text{for } \theta_D < 0) \quad \text{and} \quad R_T = 0 \,(\text{for } \theta_D \geq 0) \quad (3)$$

$$\theta_D = \theta_{PD} - P + E \quad (4)$$

where θ_D = daily soil moisture deficit required to bring the soil up to water-holding capacity, i.e., θ_{FC} (θ at −33 kPa or $\theta_{33\ kPa}$) (Cantón et al. 2010); $\theta_{PD} = \theta_D$ the previous day. The initial θ_{PD} = 131 mm (corresponding to 30 September 2003) was found by calibrating estimates until the sum of daily R_T coincided with the annual R_T. This initial calibrated θ_{PD} represents the depth of water required to bring the soil (with a soil water content of about 0%) up to θ_{FC}. This soil moisture deficit concept is useful for calculation; however, it makes no assumptions about variation in moisture content with depth (Rushton et al. 2006).

Volumetric soil water content was measured every 30 min using self-balanced impedance bridge capacitive probes (Patent no. 9401681; Vidal 1994) developed at the Estación Experimental de Zonas Áridas (CSIC, Spain). The device measures electrical impedance by two electrodes immersed in the soil that is the dielectric separation (Fig. 2e, f). Six θ measurement probes had been installed at a depth of 0.06 m since July 2003 and another six probes in the same site soil profile (3 at 0.06 m depth and 3 at less

Table 2 Cumulated monthly rainfall depth (P) and actual evapotranspiration (E), and monthly average soil moisture (θ) at 0.06 and 0.25 m depth in hydrological years 2003–2004 and 2004–2005 at the Llano de los Juanes site, used to estimate monthly R_T through the eddy covariance technique and monthly R_D through the soil water content

	2003–2004							2004–2005						
	P (mm)	E (mm)	R_T (mm)	θ (0.06 m) %	θ (0.25 m) %	R_D (mm)	R_C (mm)	P (mm)	E (mm)	R_T (mm)	θ (0.06 m) %	θ (0.25 m) %	R_D (mm)	R_C (mm)
October	80.6	24.4	0	23.6	–	0	0	17.7	11.5	0	3.8	6.3	0	0
November	109.8	19.2	20.2	30.4	–	6.5[a]	13.7[a]	16.3	8.6	0	11.9	6.6	0	0
December	47.6	16.4	34.0	34.2	–	17.2[a]	16.8[a]	70.2	12.9	0	22.3	16.6	0	0
January	2.9	13.4	0	15.4	–	0	0	0.8	6.9	0	12.2	13.6	0	0
February	19.5	20.5	8.2	18.5	15.1	0	8.2	45.8	18.5	0	20.4	16.3	0	0
March	92.1	23.2	53.0	22.5	18.3	16.4	36.6	46.0	11.1	7.8	24.8	18.8	2.3	5.5
April	88.7	41.4	54.5	22.9	18.4	27.6	26.9	3.7	22.4	0	13.8	13.5	0	0
May	50.7	35.1	19.2	18.8	15.8	13.7	5.5	0.0	39.4	0	6.2	10.0	0	0
June	6.3	66.0	0	7.6	10.6	0	0	5.1	34.5	0	4.7	9.2	0	0
July	6.5	38.4	0	3.6	7.5	0	0	0.2	23.6	0	3.7	9.2	0	0
August	0.4	17.6	0	2.9	7.2	0	0	1.2	16.3	0	2.9	–	0	0
September	2.2	10.9	0	3.3	6.9	0	0	3.1	9.4	0	3.2	–	0	0
Total	507.3	326.5	189.1			81.3	107.7	209.9	214.9	7.8			2.3	5.5
Average				17.0	12.5						10.8	12.0		

[a] Tentative estimates found by linear correlation of available R_T and R_D data

than 0.25 m depth) from 12 February 2004 to 11 July 2005 (Table 2). No probes were installed any deeper because of the large number of rock fragments in the soil. As θ was measured at two depths (0.06 and 0.25 m) only from 12 February 2004 to 11 July 2005, the R_D estimation from θ records for the two soil horizons was only for this period and for an average soil thickness of 0.35 m (Fig. 2 e, f).

R_D was quantified in rainfall event time steps from θ field data, assuming that a R_D event starts when θ field data reaches θ_{FC} until it begins to decrease below θ_{FC} again (Delin and Herkelrath 2005; Eliers et al. 2007). $\theta(t)$ = soil moisture field data at time t at the soil horizons and averaging soil water content at each depth. If $\theta(t) > \theta_{FC}$ then:

$$R_{Di} = \int_0^t (\theta(t) - \theta_{FC})\mathrm{d}t \tag{5}$$

where $\theta(t)$ is set to θ_{FC} at the end of the i recharge event. This approach was implemented by examining θ field data at 30-min time intervals ($\theta_{30\text{min}}$) during and after the n rainfall events to compute $R_D = \sum_{i=1}^{n} R_{Di}$. The maximum $\theta_{30\text{min}}$ in the soil profile recorded during the recharge event is $\theta(t)$ input used to compute R_{Di} with Eq. 5.

To insure an accurate soil saturation state, θ_{FC} was found from wet season θ records after selecting those rainfall events recorded at night and from 24 h after soil saturation. The rainfall events selected were those followed by periods with low air temperature and vapor pressure deficit close to zero. $\theta_{30\text{min}}$ records for the night after those rainfalls were examined using the Bruno et al. (2006) procedure until they became stabilized at the time when drainage had decreased and the rate of θ exchange was less than 0.001 $m^3\ m^{-3}$ in 30 min^{-1}. This is a single-store approach, which does not take water transfer between soil layers into consideration. In addition, soil moisture distribution along the soil profile, root zone distribution, soil structure, organic matter, etc., are assumed to be homogeneous, although variations such as thin calcrete subhorizons are noticeable in detail (Fig. 2e, f).

Daily R_C was computed from daily R_T and R_D by combining Eqs. 1 and 2.

Estimating total recharge at small catchment scale

Because of the small elevation range of the Fuente Alta and Enix springs' small catchments, their hydrological boundary conditions are similar to those observed in Llano de los Juanes. There is runoff only in the wettest periods (Frot et al. 2008), thus increasing R_C short downstream (Martín-Rosales et al. 2007). Recharge catchment areas are reduced and well defined (Fig. 2b). Therefore, the magnitude of R_D and R_C in R_T for average and dry rainfall years should be similar to that in Llano de los Juanes for the same hydrological time interval and altitude range, so that seasonal-to-yearly R_T rates at stand and small catchment scales can be compared to validate and estimate new data. The different spatial scale does not modify the water depth per unit surface or rate.

The environmental chemical mass balance of an atmospheric conservative solute (e.g., the chloride ion) involved in the steady-state water balance in the soil for a sufficiently long period (e.g., 1 year) can be expressed by transforming Eq. 1 (Custodio and Llamas 1976–1983; Wood and Sanford 1995; Custodio et al. 1997; Scanlon et al. 2006) into:

$$P \cdot C_P = R_D \cdot C_{RD} + R_C \cdot C_{RC} \pm F \tag{6}$$

where E (chloride-free water vapor) is not considered; C = average chloride concentration of each water balance term during the sampling interval (for P), or the average concentration from a specific number of samples in the period (for R_D and R_C) (specified by the subscripts). F = other sources of chloride, such as lithologic contribution of chloride or minerals precipitated in the soil during previous long dry periods.

Under steady-state environmental and land use conditions, discharge in local springs is assumed equal to the average R_T in the catchment with unknown fractions of R_D and R_C, which are assumed to be well mixed in the unsaturated zone before discharge. It is assumed that (1) recharge is produced after a relatively short transit time through the unsaturated zone and daily-to-weekly chloride influxes from soil water moisture are entirely incorporated into the groundwater sampling interval, as will be described below; (2) advective mixing in the aquifer does not affect groundwater sampling; (3) F is negligible; so, seasonal R_T was estimated by the atmospheric chloride mass balance (CMB) method in both small catchments by transforming Eq. 6 into:

$$P \cdot C_P = R_T \cdot C_{RT} \tag{7}$$

where $A_P = P{\cdot}C_P$ the atmospheric bulk chloride deposition in the study period (g m^{-2}) or the yearly rate from adding successive periods to complete a year (g m^{-2} $year^{-1}$) (Alcalá and Custodio 2008a). A_P includes contribution of chloride from incoming marine aerosols from wet deposition by precipitation (rainfall, snow, frost) plus dissolved solutes from local dry fallout (Alcalá and Custodio 2008b).

The groundwater sampling frequency depends on the average turnover time of groundwater stored in perched aquifers; under piston (plug) flow conditions, it is estimated as:

$$\tau = (b \cdot A \cdot S)/(K \cdot h) \tag{8}$$

where τ average turnover time of groundwater (days); b an aquifer geometry factor (dimensionless) that averages 1.5

for circular sector-shaped catchments such as the one studied here (Fig. 1) (Custodio and Llamas 1976–1983); A aquifer surface (m^2); S aquifer storage coefficient (drainable porosity for unconfined aquifers, dimensionless); K hydraulic conductivity (m day^{-1}); h average saturated thickness (m).

Taking A from Table 1, S = 0.15 and K = 80 m day^{-1} from Domínguez (2000), and h = 15 m and h = 25 m for Fuente Alta and Enix catchments after direct field observations on the aquifer geometry, τ averages for 1.5 months for both springs. So, A_P was monitored periodically within this time interval (Table 3) and the discharge flow of selected springs was measured manually, collecting two to three groundwater samples to determine the average discharge-weighed C_{RT} content in these time intervals (Table 4).

Atmospheric bulk deposition was collected at the Atalaya and Cajilón rain gauge stations from October 2003 to October 2005 in monthly-to-quarterly time intervals (Fig. 1; Table 3). The rainwater samples, preserved by paraffin oil during the rainfall collection period, were later analyzed for their chloride content.

The chloride concentration in filtered, unacidified rainwater and groundwater samples (mg L^{-1}) was analyzed by the Geological Survey of Spain (IGME) Laboratory following the EPA 3001A method (Hautman and Munch 1997) with a DIONEX 600® high-performance liquid (anionic) chromatograph, providing a precision of ± 0.015 mg L^{-1} for chloride content below 0.5 mg L^{-1}, which is usual in little mineralized rainwater samples (Alcalá and Custodio 2008b).

Results

R_T at stand scale

In Llano de los Juanes, daily water balances for the average rainfall year 2003–2004 and the unusually dry 2004–2005 (Fig. 3) were added to obtain monthly and yearly values to explain the results at different time scales (Fig. 4a; Table 2). The water balance at monthly intervals shows strong variations in E in both 2003–2004 and 2004–2005. Monthly R_T ranges from 54.5 mm in April 2004 down to 0 in most of the months studied (Table 2). The highest E rates were measured in late spring and the first half of the 2003–2004 summer, mainly matching the vegetation growing period and high radiative energy inputs typical of this season; R_T is almost negligible. Almost 70% of the annual R_T in 2004 was found from February to May; in 2005 all of the R_T was in March. No R_T was recorded in April 2005. R_T was 189.1 mm in the year 2003–2004 (0.37 of rainfall), and 7.8 mm in the year 2004–2005 (Table 2; Fig. 4). These results were compared with the small catchment-scale R_T estimated by the CMB method.

Table 3 Operating period at the Atalaya (36°52′36″N, 2°45′28″W, 1,702 m a.s.l.) and Cajilón (36°50′28″N, 2°47′27″W, 438 m a.s.l.) open rain gauge stations

Station	Sampling period		n	P (mm)	C_P (mg L^{-1})	A_{Pi} (g m^{-2})	a_i
	From	To					
Atalaya	01-Oct-03	08-Jan-04	99	245.0	0.98	0.24	1.50
	08-Jan-04	07-Apr-04	90	131.0	1.87	0.24	1.68
	07-Apr-04	02-Jul-04	86	130.5	1.58	0.21	1.48
	02-Jul-04	30-Sep-04	90	12.5	3.56	0.04	0.31
	01-Oct-04	01-Jan-05	92	113.0	1.45	0.16	1.10
	01-Jan-05	04-Apr-05	93	98.0	1.98	0.19	1.29
	04-Apr-05	06-Jul-05	93	12.0	3.65	0.04	0.29
	06-Jul-05	30-Sep-05	86	8.5	5.12	0.04	0.31
Cajilón	24-Oct-03	05-Jan-04	73	170.6	1.72	0.29	2.99
	05-Jan-04	26-Apr-04	112	148.1	1.19	0.18	1.17
	26-Apr-04	25-Aug-04	121	58.2	2.40	0.14	0.86
	25-Aug-04	25-Dec-04	122	111.6	1.04	0.12	0.71
	25-Dec-04	20-Mar-05	85	85.3	2.03	0.17	1.51
	20-Mar-05	02-May-05	43	3.2	8.20	0.03	0.45
	02-May-05	20-Oct-05	171	9.0	5.70	0.05	0.22

P rainfall depth and C_P average chloride content in bulk deposition used to calculate A_{Pi} atmospheric bulk chloride deposition in the period; a_i for A_{Pi} calculations (dimensionless); n number of days with a continuous precipitation record analyzed

Table 4 Operating period and discharge-weighted C_{RTi} content in the period in Fuente Alta and Enix catchment springs; *n* number of days covered; s number of samples used to calculate C_{RTi}; A_{Pi} average bulk chloride deposition at Fuente Alta and Enix springs estimated from data from the Atalaya and Cajilón stations during the period (Table 3) after correcting data sets for elevation; R_{Ti} potential recharge in the period; *Q* average discharge flow

Spring	Sampling period		*n*	C_{RTi} (mg L^{-1})	s	A_{Pi} (g m^{-2})	R_{Ti} (mm)	*Q* (L min^{-1})
	From	To						
Fuente Alta Spring	01-Oct-03	08-Jan-04	99	2.57	2	0.24	92.2	5.36
	08-Jan-04	07-Apr-04	90	4.42	2	0.25	56.3	3.78
	07-Apr-04	02-Jul-04	86	3.83	2	0.21	55.5	4.14
	02-Jul-04	30-Sep-04	90	9.82	2	0.04	4.5	0.28
	01-Oct-04	01-Jan-05	92	5.66	2	0.17	29.4	1.86
	01-Jan-05	04-Apr-05	93	15.40	2	0.20	12.7	0.67
	04-Apr-05	06-Jul-05	93	26.08	2	0.04	1.7	0.09
	06-Jul-05	30-Sep-05	86	28.97	2	0.04	1.5	0.08
Enix Spring	01-Oct-03	08-Jan-04	99	4.92	2	0.27	55.8	5.42
	08-Jan-04	07-Apr-04	90	3.47	2	0.20	57.7	6.74
	07-Apr-04	02-Jul-04	86	8.84	3	0.13	14.8	2.12
	02-Jul-04	30-Sep-04	90	13.46	2	0.05	3.6	0.47
	01-Oct-04	01-Jan-05	92	35.22	2	0.13	3.8	0.50
	01-Jan-05	04-Apr-05	93	47.79	3	0.18	3.8	0.46
	04-Apr-05	06-Jul-05	93	52.32	3	0.03	0.6	0.08
	06-Jul-05	30-Sep-05	86	57.43	2	0.05	0.8	0.11

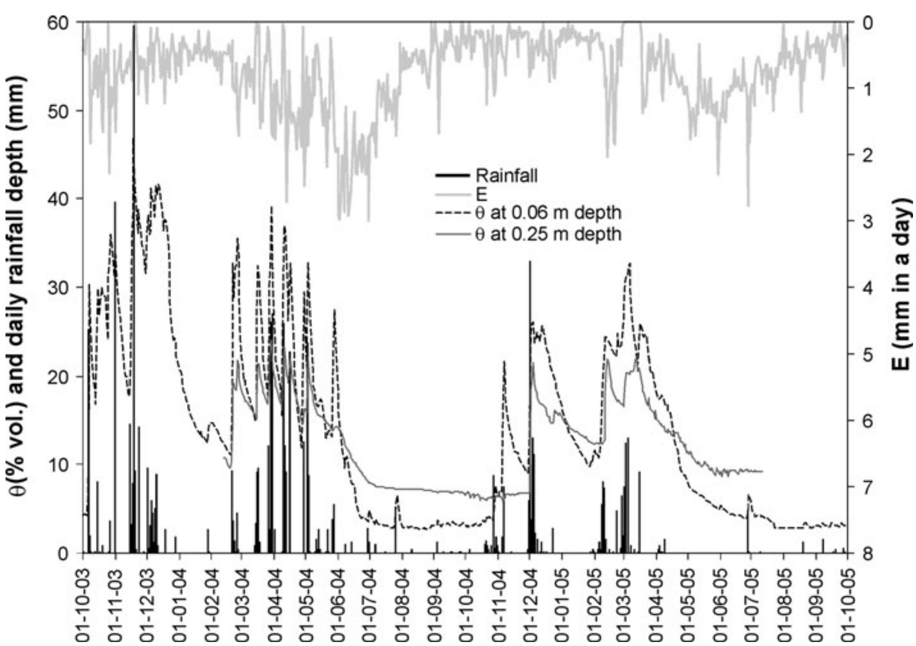

Fig. 3 Daily rainfall, *E* (actual evapotranspiration) and total soil water content (θ) at depths of 0.06 and 0.25 m in the hydrological years 2003–2004 and 2004–2005 at the Llano de los Juanes site

R_D at stand scale

At Llano de los Juanes, R_D was computed at a rainfall event time scale from 12 February 2004 to 7 July 2005 (Figs. 2e, f, 3; Table 2). R_D was around 57.6 mm from winter to summer in 2003–2004. In the autumn of 2003, θ field data at 0.25 m depth was not measured and R_D could not be estimated (Table 2). However, during this period, the rainfall depth was higher than *E*, and R_T was around 54 mm, suggesting that diffuse recharge could have taken place. A linear correlation of R_T and R_D from the adjacent periods with data for the same variables was assumed to fill the gap in R_D estimates for that time interval. A yearly R_D of ~81.3 mm (0.16 of rainfall) was tentatively estimated.

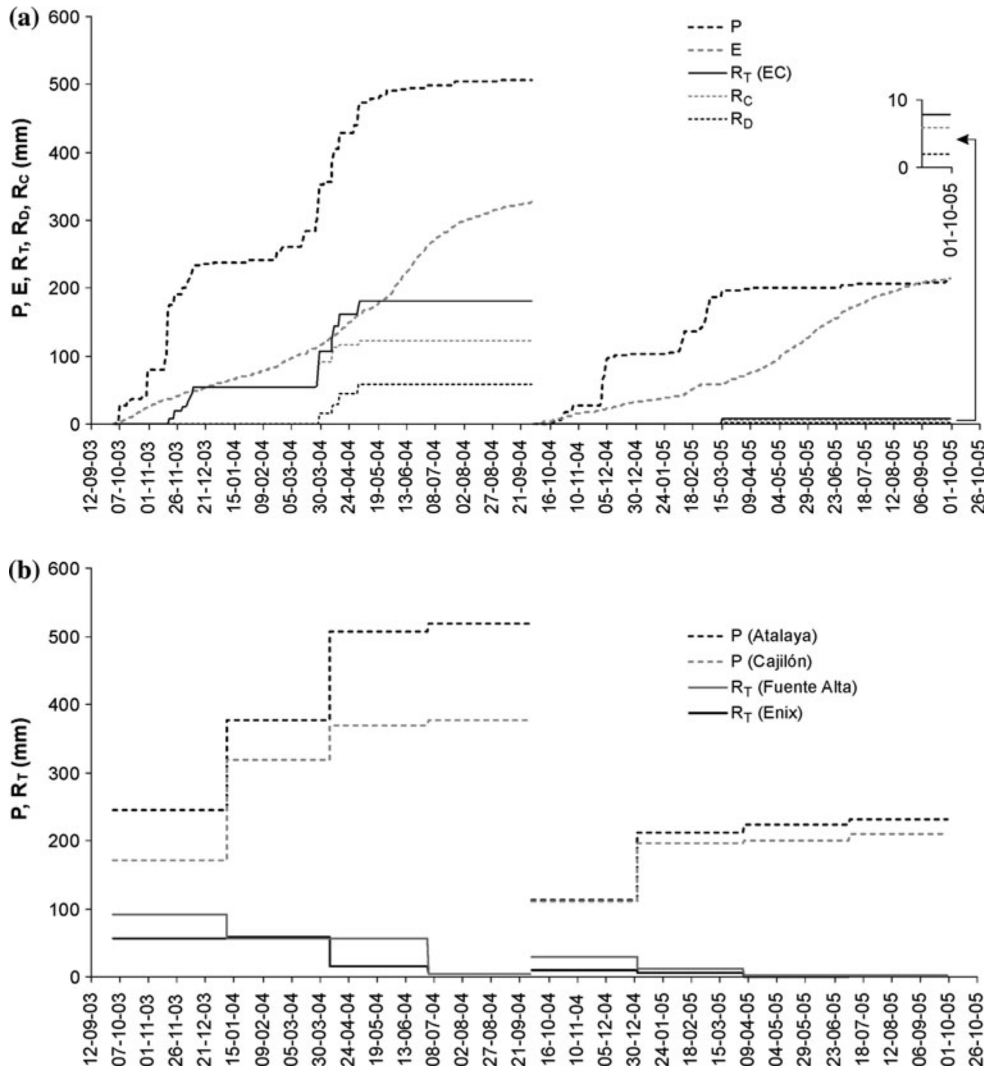

Fig. 4 *P* (precipitation), *E* (actual evapotranspiration) and R_T, R_D and R_C recharge components for hydrological years 2003–2004 and 2004–2005. **a** Cumulative daily *P*, *E* (from eddy covariance technique, EC) and R_T, and R_D and R_C at Llano de los Juanes; R_D was computed from 1 September 2004 to 30 September 2005, with information on R_C only for that period. **b** Cumulative seasonal *P* at the Atalaya and Cajilón open rain gauges and seasonal R_T at Fuente Alta and Enix catchment springs, after correcting for partial chloride bulk deposition for elevation using measurements from the Atalaya and Cajilón stations

Daily θ field data remained under higher water tensions ($\theta < 10\%$) during most of 2004–2005 and R_D was only 2.3 mm (0.01 of rainfall) (Figs. 3, 4; Table 2).

Time required for R_D generation

The average time required for R_D generation after the start of a rainfall event is valuable information for estimating the expected delay in R_D relative to R_C involved in groundwater discharge from large springs and pumping wells when both fractions are taken into account. This time was found from daily θ field data monitored at depths of 0.06 and 0.25 m after one rainfall event of about 53 mm that took place in spring (28–29 March 2004) (Fig. 5). Spring is the temperate period of the year, with moderate-to-high daily *E* rates. Most of R_T and R_D took place during this season (Table 1).

This rainfall event produced an R_D of around 16.4 mm. Antecedent θ field data was 15% at a depth of 0.06 m and 10% at 0.25 m. The day afterward, θ at 0.25 m reached a peak of 36%, slightly exceeding the experimental $\theta_{FC} = 35\%$ measured in the field. At 0.06 m, downward water depletion was fast for up to 4 days after the rainfall event and, in the following days, θ was as much as 34% and R_D was assumed to be negligible (Fig. 5).

These and other figures used to compute R_D from single rainfall events show that in these thin soils, true R_D is a slower dynamic process most influenced by daily *E* rates with a time response below the root zone from less than 1 day, and even hourly to around a week, whereas R_C generation is simultaneous with rainfall events according to direct observation in the field and data found by Frot et al. (2008).

R_T at small catchment scale

Monthly-to-quarterly rainfall depth *P* (mm) and the average C_P concentration (mg L^{-1}) provided the atmospheric bulk chloride deposition for the period (A_{Pi}, g m^{-2}) at the Atalaya and Cajilón stations. The regularity of partial A_{Pi} data during the study period was checked by using the dimensionless ratio $a_i = (365{\cdot}A_{Pi})/(A_{PT}{\cdot}n)$ for sampling intervals i along a total duration of n days (Alcalá and Custodio 2008a), where A_{PT} deposition over the whole sampling period (e.g., 1 hydrological year) by adding up partial A_{Pi} data (Table 3). a_i is around 1.0 when deposition tends to be uniform in time and ranges from less than 2 in spring and autumn to 0.2 in summer with similar variation in time between stations, which allows data trends to be compared for regionalized estimates. In 2003–2004, yearly A_P was 0.73 and 0.89 g m^{-2} year^{-1} at the Atalaya and Cajilón stations, respectively, while in the year 2004–2005, A_P was 0.45 and 0.47 g m^{-2} year^{-1} (Table 3; Fig. 6).

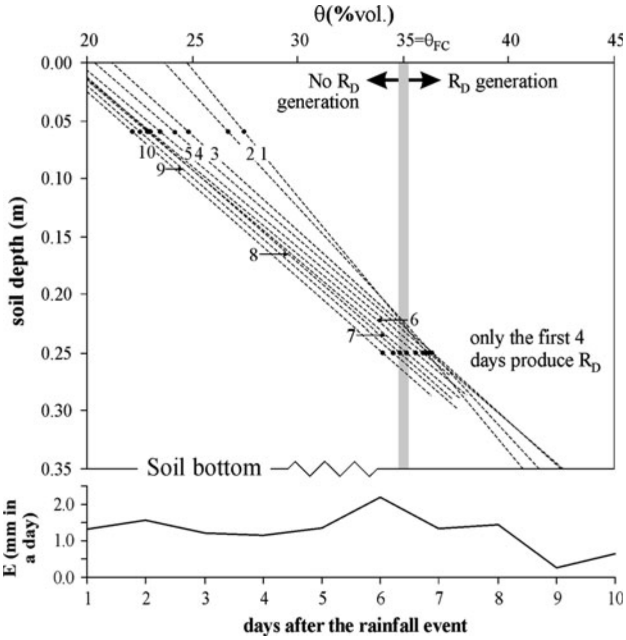

Fig. 5 Daily total soil water content (θ) field data at depths of 0.06 and 0.25 m (*solid circles*) after a rainfall event of about 53 mm on 28–29 March 2004 with the first 4 days after start of the rainfall event with $\theta \geq \theta_{FC} = 35\%$ at 0.25 m producing an R_D of about 16 mm. *1–10* on *dashed lines* are the days after the rainfall event

From 3- to 4-year long series, Alcalá et al. (2007) and Alcalá and Custodio (2008a) found average A_P from 5 to 6 g m^{-2} year^{-1} on the local coast (Adra and Almería; Fig. 1) to 0.5–0.7 g m^{-2} year^{-1} on the Sierra de Gádor Mountains summit. These figures show a sharp gradient from over 0.5 g m^{-2} year^{-1} km^{-1} on the coastal fringe and decreasing exponentially inlandwards to around 0.05 g m^{-2} year^{-1} km^{-1} on summits, depending on how exposed these windy areas were to incoming marine fronts and the relative chloride contribution from dry fallout and other anthropogenic sources into bulk deposition (Alcalá and Custodio 2008b). The spatial gradient of A_P is the result of the spatial precipitation gradient, which doubles from the coastal fringe to summit areas, and the average C_P

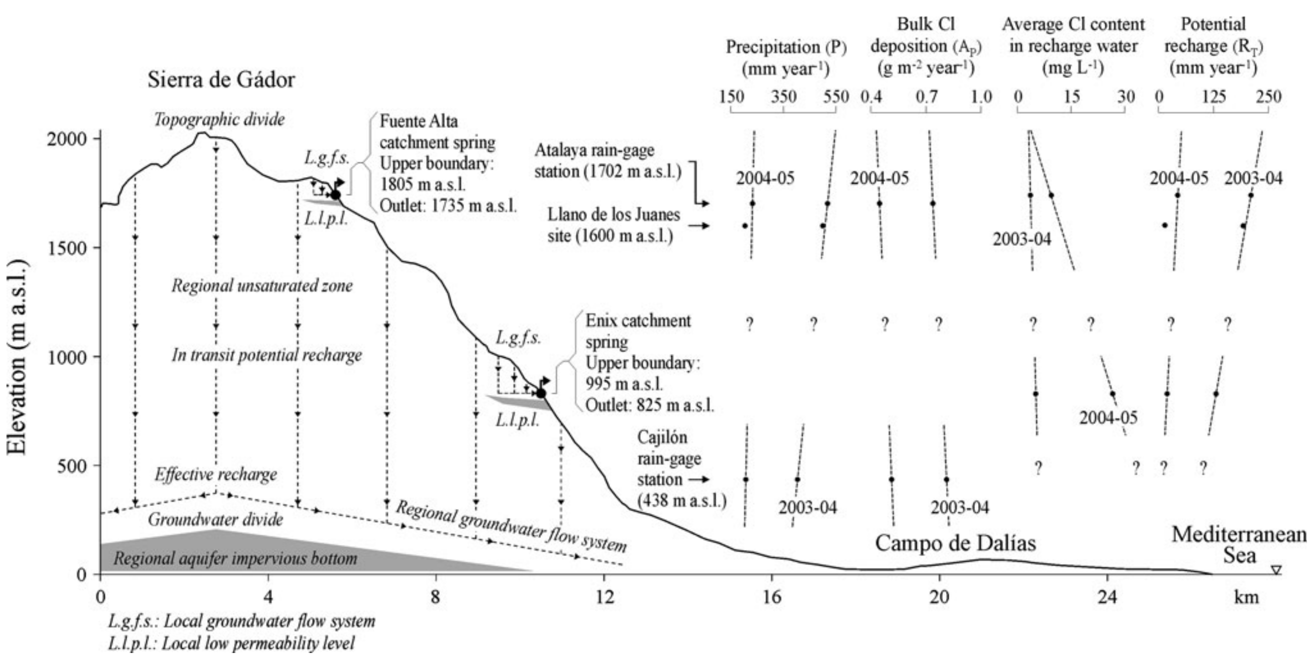

Fig. 6 Elevation and location of Fuente Alta and Enix local springs, Atalaya and Cajilón rain gauge stations and Llano de los Juanes site projected over a synthetic topographic cross section from the coast up to the Sierra de Gádor Mountains summit. The simplified regional hydrogeological framework is overimposed, where *dashed lines* and *arrows* identify regional R_T flow paths through the unsaturated zone and local R_T flow paths integrated in the outlet of Fuente Alta and Enix catchment springs. Linear variation with altitude of yearly P, A_P and R_T rates and discharge-weighted C_{RT} content for 2003–2004 and 2004–2005 are included to provide altitudinal gradients of A_P and C_{RT} in both catchment springs

spatial gradient, which decreases one order of magnitude from 15 ± 10 to 2 ± 1.5 mg L^{-1} along this path. The spatial gradient of A_P becomes linear around 10–15 km from the coast (Alcalá and Custodio 2008a). This behavior enables the spatial gradient to be expressed as an altitudinal gradient for estimating partial A_{Pi} at the Fuente Alta and Enix catchment springs from A_{Pi} measured at the Atalaya and Cajilón stations.

Temporal (seasonal) R_{Ti} at both Fuente Alta and Enix catchment springs results from A_{Pi} values estimated there, after correcting the series for elevation and the average C_{RT} measured in those periods, C_{RTi} (mg L^{-1}) (Table 4, Fig. 6). At Fuente Alta Spring, R_{Ti} varies from ~90 mm in autumn 2003 to ~1.5 mm in summer 2005, while at Enix Spring, R_{Ti} varies from ~60 mm in spring 2004 to less than 1 mm in summer 2005 (Table 4). Yearly R_T was 209 and 132 mm in the year 2003–2004, and 44 and 9 mm in the year 2004–2005 at the Fuente Alta and Enix springs, respectively (Figs. 4, 6; Table 4).

Discussion

Environmental meaning of recharge

Yearly small catchment-scale R_T estimated by the CMB and SWB methods with E measured using the EC technique at one well-instrumented site ranges from 0.35 to 0.40 of cumulative rainfall in the average rainfall year 2003–2004. The difference between the two procedures is around 5% for a similar range of elevation, after correcting datasets for elevation (Fig. 6). In the dry rainfall year 2004–2005, R_T increases from less than 0.05 of rainfall at mid-elevation (from 800 to 1,200 m a.s.l.) to 0.20 at high altitudes (over 1,700 m a.s.l.) on the southern slope of the Sierra de Gádor Mountains, with a similar difference between procedures. This means that both the areal CMB and the locally detailed EC technique for implementing the SWB are quite accurate methods to estimate from moderate-to-low R_T rates under contrasting climate conditions. This enables estimates by physical and tracer techniques to be validated, new estimates to be acquired from other non-instrumented local springs, gaps in information and data series to be filled in, etc. Similar assumptions have been reported by Lerner et al. (1990), Simmers et al. (1997), Wood et al. (1997), Scanlon et al. (2006) and most other authors by using the CMB and accurate SWB methods for R_T estimation in both homogeneous and heterogeneous, flat and hilly semiarid areas. Environmental and artificial radio-isotopic techniques, hydrodynamics methods or those based on groundwater flow modeling have been used to complement and compare recharge estimates in similar ungauged areas little affected by human activity (Simmers et al. 1997). In these cases, the accuracy of R_T estimates by SWB methods largely depend on the precision in estimating E when it is close to P, while the CMB method becomes a routine, accurate procedure for yearly R_T rates of less than 0.05 of cumulative rainfall when runoff is negligible. This paper shows a similar situation in scattered local, perched springs in sloping areas with a well-defined recharge catchment area where R_T can be assessed by the CMB method, if there are no significant deep loses.

The common 1- to 3-day rainfall events recorded during the average rainfall year 2003–2004 induce an R_D generation time response of less than 1 day to around a week, depending on the frequency and depth of rainfall events. R_D was around 0.16 of rainfall in the average rainfall year 2003–2004 and 0.01 in the dry year 2004–2005, since the soil water content was used to satisfy soil and plant water demand. This magnitude and time required for generation is in agreement with those found by Keese et al. (2005) and Eliers et al. (2007) in semiarid zones of Texas (USA) and NE Nigeria, respectively, under similar daily P, E and soil moisture condition patterns. R_C generation has a delay from negligible to a few hours of the rainfall event, both in average and dry rainfall years (Frot et al. 2008).

The R_C/R_D ratio increases with greater aridity, modulating the average discharge flow rate and the hydrochemistry of local springs with very low water–rock interaction. The salinity variation, traced by the conservative C_{RT} content, measured in the Fuente Alta and Enix catchment springs is controlled by the relative R_C (less affected by saline evapoconcentration) and R_D (more affected by saline evapoconcentration) contributions induced by local climate. The average yearly C_{RT} ratio between 2003–2004 and 2004–2005 in both Fuente Alta and Enix springs was 0.27 and 0.16, respectively. This ratio (1) seems to increase downslope as climatic aridity decreases with elevation; (2) provides the absolute salinity factor gained by local recharge water at those places (or elevations) (~3.5 in Fuente Alta and ~6 in Enix catchment springs, respectively) between an average rainfall year and a following dry one; (3) can be used for modeling how much R_T is expected to actually reach the regional water table as net recharge after a dry period if there are accurate atmospheric bulk deposition measurements available along the slope (Alcalá et al. 2007).

Because extreme climate evolution may increase or decrease human stress on groundwater, the response of both groundwater storage and baseline quality to recharge input and mechanisms may be significant when climate cycles coincide with positive (wet/cool) or negative (dry/warm) phases (De Vries and Simmers 2002; Gurdak et al. 2007).

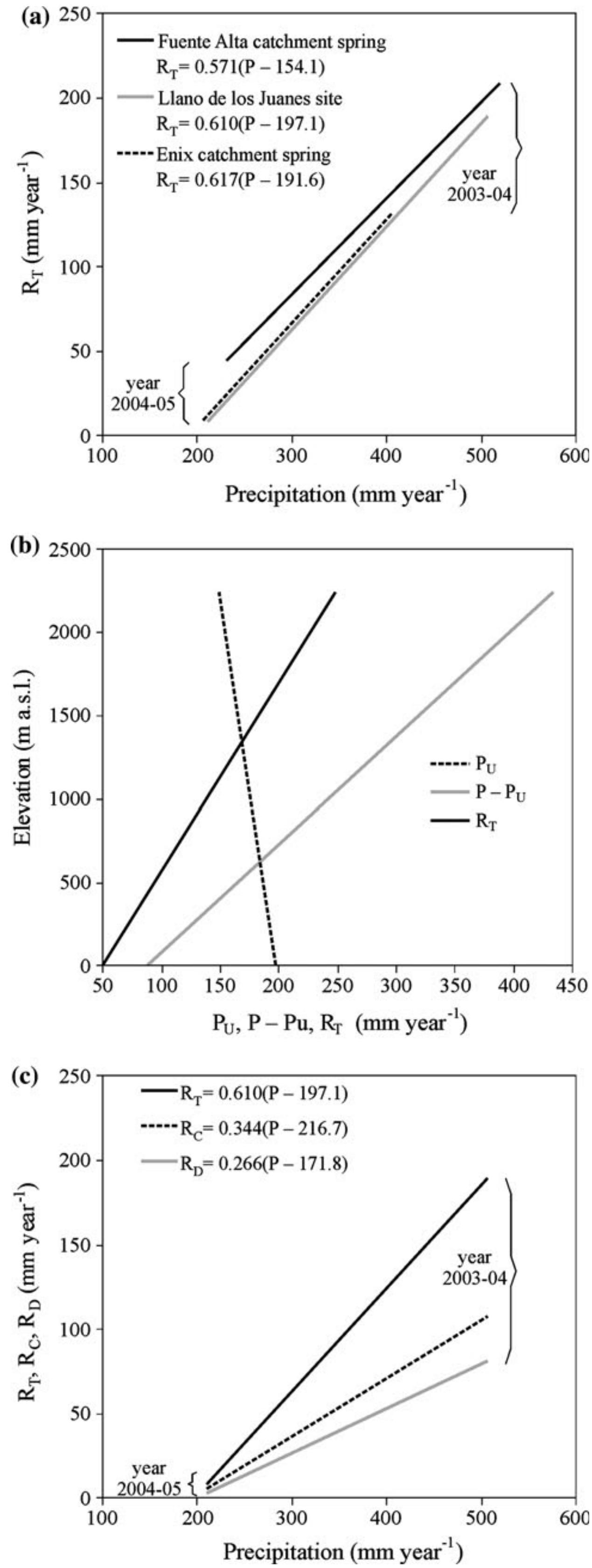

Fig. 7 **a** Empirical relationships for yearly P versus yearly $R_T = \alpha(P - P_U)$ in Fuente Alta and Enix catchment springs, and at the Llano de los Juanes site in the average rainfall year 2003–2004 and the dry rainfall year 2004–2005. **b** Extended evolution in P_U, $P - P_U$ = effective rainfall and yearly R_T (mm year^{-1}) for the southern slope of the Sierra de Gádor Mountains in the average rainfall year 2003–2004. **c** Empirical relationships for yearly P versus yearly R_T, R_D and R_C at the Llano de los Juanes site

Parameterizing recharge

Yearly P and R_T calculated using the CMB method in the Fuente Alta (1,770 m a.s.l. average altitude) and Enix (910 m a.s.l. average altitude) small catchment springs, and by the SWB method in Llano de los Juanes (1,600 m a.s.l.) in both 2003–2004 and 2004–2005 were plotted to parameterize yearly R_T as an empirical function of P at those sites. A linear relationship $R_T = \alpha(P - P_U)$ for $P_U \leq P$ was used in all cases (Fig. 7a), as in Falkland and Custodio (1991) and Ross et al. (2001) to define yearly recharge as a fraction of yearly rainfall in other dry, temperate and wet regions.

P_U and α (dimensionless) are parameters that are usually the result of fitting long-term P and R_T data from dry, wet and average rainfall years. It is assumed that data sets for clusters of dry, wet and average rainfall years follow a normal distribution. These data sets can then be studied statistically to provide low, mean and high thresholds for P_U and α, as well as their confidence level. But in this case, only one dry and one average rainfall year were studied to characterize P_U and α. Therefore, significance was verified by studying the long-term data from La Zarba meteorological station, which has a 30-year daily precipitation record. The two dry and average rainfall years were compared with clustered dry and average rainfall year data sets in the La Zarba long-record series. Results validate 0.90 of the variance. Therefore, P_U and α from these two single years explain the steady condition of dry and average rainfall years with one standard deviation (1σ) of about $\pm$ 0.05.

In Fig. 7a, α is the slope of the straight lines. Theoretically, it ranges from 0, when no precipitation is transformed into recharge, to 1, when all precipitation is transformed into recharge. Adjusted α decreases slightly with elevation between the study sites, from 0.617 at the Enix catchment spring to 0.571 at the Fuente Alta catchment spring (Fig. 7a). This is an absolute deviation of less than 0.05, which seems nonsignificant if errors are calculated. Nevertheless, this deviation may also mean a slightly nonlinear condition for R_T generation from rainfall in that altitude range on the southern slope of the Sierra de Gádor Mountains, as found by Contreras et al. (2008) at around

1,200 m a.s.l., probably induced by the change from semiarid-to-subhumid climate conditions. Thus, α provides information about stable site conditions considered, such as topography, lithology, fracturation and karstic development, which are also the most relevant factors controlling R_C generation.

P_U is the intercept of the straight lines defined in Fig. 7a, which is a threshold precipitation below which there is no recharge. P_U decreases with elevation (Fig. 7a, b), in good agreement with most R_T events from the highest rainfall event frequency and depth at high altitude in the Sierra de Gádor Mountains, and the lower daily E rates induced by low temperature (Contreras et al. 2008; Frot et al. 2008). P_U seems to depend on variable conditions accounted for at those sites, such as fluctuations in soil water content that control R_D generation, as well as rainfall event frequency and depth, which control both the R_D (nonlinearly with rainfall depth) and R_C (linearly) components at each elevation range. Whereas in flat areas, P_U is expected to be steady or less variable, because the spatial rainfall distribution and soil properties are more homogeneous, in sloping areas P_U measured at any given place represents a single and characteristic value for that specific range of elevation.

The linear relationship between R_T and P means that $R_T = 0$ for $P = P_U$. This is true for true R_D, but not necessarily for R_C, especially if local runoff conditions allow rainfall events to be concentrated in small preferential infiltration areas. The combination of R_C and lower R_D rates for dry seasons and years may be an additional linear relationship with smaller α intersecting the former linear relationship at some point above P_U. This is what seems to happen in sandy areas in Doñana, southwestern Spain (Custodio 2009a).

The fact that P_U seems to decrease slightly with elevation at the study sites, integrating R_T estimates from stand to small catchment scales, and where recharge is evaluated by alternative methods, suggests that variation in the R_D/P and R_C/P ratios with altitude can also be possible for that elevation range, although further studies for longer periods are needed to verify and quantify this assumption, taking into account the possibility of different P_U and α values in non-monitored foot slope areas. So far, R_T, R_D and R_C have been determined for at least two average and dry rainfall years only in Llano de los Juanes (Fig. 7c). The experimental data for $\alpha_{RT} \geq \alpha_{RC} \geq \alpha_{RD}$ seems to imply a parameterized R_D–P, R_C–P and R_T–P-pair data variation at that site (Fig. 7c).

Just as α_{RT} (Fig. 7a), if α_{RD} and α_{RC} are stable or somewhat variable along the slope, the R_C fraction could also be regionalized as a function of P for a well-defined variation in rainfall with elevation, while R_D fraction parameterization requires additional daily soil experimental data. This would roughly estimate the relative contributions of the true R_D and R_C fractions in the discharge flow of large springs and penetrating pumping wells that incorporate recharge from different parts of the territory and different elevations. Replicating the estimation of R_T and R_D at most sites could provide most of the R_T, R_D and R_C data for regional P_U and α parameters along the southern slope of the Sierra de Gádor Mountains. This is a line of research to be continued in the coming years, taking instrumental and environmental uncertainties of involved terms into account.

What has been done refers to carbonate terrain with thin, but not negligible, pedologic soil, dispersed vegetation cover and conditions for establishing a soil balance of rainfall, with possible fast recharge through cracks. The fact that the CMB method gives reasonably good results points his suitability for applying under similar conditions to other areas when recharge water chloride content is from boreholes just obtaining the water table. Part of recharge may be long delayed when thick unsaturated zones exist, and the borehole penetration, even if small, means mixing of water of different age. Thus, the balance results do not correspond to seasonal or the yearly recharge, but a compound of several years if mixing during recharge or when sampling is important (Custodio et al. 1997; Alcalá et al. 2007; Custodio 2009b).

The CMB allows interpreting the effect of surface water recharge in foothills if it is dispersed, but does not allows considering concentrated recharge in cracks and large geological discontinuities.

Really, carbonate areas, and especially carbonate massifs, are territorially very variable, from areas with soil and vegetation to bare bedrock areas. This makes the SWB methods difficult to apply except if a detailed geographical, geological and climatic discretization is done, each with the appropriate parameters. Calibration with large spring flows or water table fluctuations is a difficult task, and often this cannot be carried out due to inexistent data and unfavorable hydrogeological conditions. Then, the CMB method is a useful tool for average, long-term recharge conditions.

Conclusions

This work provides a conceptually simple way to assess seasonal-to-yearly R_T in ungauged mountain carbonate aquifers by the CMB method applied to small catchment springs with external validation by means of stand-scale R_T estimates by applying accurate SWB methods (e.g., the EC technique for estimating E in this paper). R_T estimated by the CMB method in small catchment springs is a representative fraction (a sample) of the total recharge in transit intercepted by a low permeability layer before reaching the regional water table as future net recharge. The R_T estimated by the SWB is potential total recharge below the root zone produced at that stand scale. For the same range of elevation, the difference between the methods is less than 5% for both average and dry rainfall years, neglecting the effect of integrated surface in estimates.

The linear parameterization of yearly P–R_T pair data in the study area shows a slight nonlinear condition for R_T generation from rainfall along the southern slope of the Sierra de Gádor Mountains. The poorly defined conjunction of climate (semiarid to subhumid, increasing rainfall event frequency and rainfall depth with elevation), thin soils, profuse soil cracks and discontinuities in these densely fractured rocks and bare bedrock become the most relevant features causing wide spatiotemporal variation in the true R_D and R_C fractions, which mix in variable proportions and neither definitively explained nor quantified. Yearly true R_D in R_T was quantified at around 0.16 of rainfall in 2003–2004 and around 0.01 in 2004–2005, when soil moisture fell below the field capacity to satisfy soil and plant water demands. Under steady-state conditions, yearly R_C is the difference between yearly R_T and R_D.

Experience gained in mechanisms and recharge rates in the Sierra de Gádor Mountains is a source of knowledge for other mid-latitude Mediterranean regions with similar geology, orography and climate. It helps to (1) validate the magnitude of R_T from stand to small catchment scales under both average rainfall and extremely dry conditions, and (2) parameterize yearly P–R_T pair data with elevation, to explain the impact of climatic aridity on groundwater resources of similar ungauged carbonate massif aquifers with negligible runoff and limited or null surface water resources.

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References

Alcalá FJ, Custodio E (2008a) Atmospheric chloride deposition in continental Spain. Hydrol Process 22(18):3636–3650

Alcalá FJ, Custodio E (2008b) Using the Cl/Br ratio as a tracer to identify the origin of salinity in aquifers in Spain and Portugal. J Hydrol 359(1–2):189–207

Alcalá FJ, Custodio E, Contreras S, Araguás LJ, Domingo F, Pulido-Bosch A, Vallejos Á (2007) Influencia de la aridez climática, la altitud y la distancia al mar sobre el contenido en cloruro y en δ^{18}O del agua de recarga y del agua subterránea en macizos carbonatados costeros del SE peninsular español. Caso de Sierra de Gádor. In: Pulido-Bosch A, López-Geta JA, Ramos G (eds) Coastal aquifers intrusion technology: Mediterranean countries (TIAC'07), vol 1. IGME, Madrid, pp 871–885

Anderson DE, Verma SB, Rosenberg NJ (1984) Eddy correlation measurements of CO_2, water vapour and sensible heat fluxes over a crop surface. Boundary Layer Meteorol 29:167–183

Andreo B, Vías J, Durán JJ, Jiménez P, López-Geta JA, Carrasco F (2008) Methodology for groundwater recharge assessment in carbonate aquifers: application to pilot sites in southern Spain. Hydrogeol J 16(5):911–925

Bruno RD, da Rocha HR, de Freitas HC, Goulden ML, Miller SD (2006) Soil moisture dynamics in an eastern Amazonian tropical forest. Hydrol Process 20:2477–2489

Cantón Y, Villagarcía L, Moro MJ, Serrano-Ortiz P, Were A, Alcalá FJ, Kowalski AS, Solé-Benet A, Lázaro R, Domingo F (2010) Temporal dynamics of soil water balance components in a Mediterranean carbonate range in SE Spain: estimation of potential recharge. Hydrol Sci J (accepted)

Contreras S, Boer MM, Alcalá FJ, Domingo F, García M, Pulido-Bosch A, Puigdefábregas J (2008) An ecohydrological modelling approach for assessing long-term recharge rates in semiarid karstic landscapes. J Hydrol 351:42–57

Cruz-Sanjulián J, Araguás L, Rozanski K, Benavente J, Cardenal J, Hidalgo C, García-López S, Martínez-Garrido JC, Moral F, Olías M (1992) Sources of precipitation over south-eastern Spain and groundwater recharge. An isotopic study. Tellus 44B:226–236

Custodio E (2009a) Estimation of aquifer recharge by means of atmospheric chloride deposition balance. Contributions to Science I 5(2)

Custodio E (2009b) Recarga a los acuíferos extensos a partir de la deposición atmosférica de cloruros y de la temperatura del terreno. Boletín Geológico y Minero 120(4):631–640

Custodio E, Llamas MR (1976–1983) Hidrología Subterránea. Omega, Barcelona

Custodio E, Llamas MR, Samper J (1997) La evaluación de la recarga a los acuíferos en la Planificación Hidrológica. IAH Spanish Chapter/ITGE, Madrid

De Vries JJ, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. Hydrogeol J 10(1):5–17

Delin GN, Herkelrath WN (2005) Use of soil moisture probes to estimate ground water recharge at an oil spill site. J Am Water Resour Assoc 41(6):1259–1277

Domínguez P (2000) Funcionamiento hidrogeológico y mecanismos de intrusión marina en sistemas carbonatados de estructura compleja: aplicación al Acuífero Inferior Noreste (AIN) del Campo de Dalías (Almería). Ph.D. Thesis. Universitat Politècnica de Catalunya

Eliers VHM, Carter RC, Rushton KR (2007) A single layer soil water balance model for estimating deep drainage (potential recharge): an application to cropped land in semi-arid north-east Nigeria. Geoderma 140:119–134

Falkland A, Custodio E (1991) Hydrology and water resources of small islands: a practical guide. Studies and Reports in Hydrology, 49. UNESCO, Paris

Frot E, Van Wesemael B, Solé-Benet A, House MA (2008) Water harvesting potential in function of hillslope characteristics: a case study from the Sierra de Gador (Almeria province, south-east Spain). J Arid Environ 72(7):1213–1231

Gee GW, Hillel D (1988) Groundwater recharge in arid regions: review and critique of estimation methods. Hydrol Process 2:255–266

Gurdak JJ, Hanson RT, McMahon PB, Bruce BW, McCray JE, Thyne GD, Reedy RC (2007) Climate variability controls on unsaturated water and chemical movement, High Plains Aquifer, USA. Vadose Zone J 6(2):533–547

Hautman DP, Munch DJ (1997) EPA 300 1. Determination of inorganic anions in drinking water by ion chromatography. Revision 1.0. USEPA, Office of Water. EPA, Cincinnati

Keese KE, Scanlon BR, Reedy RC (2005) Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. Water Resour Res 41:W06010. doi:10.01029/02004WR003841

Kovalevskii VS (2007) Effect of climate changes on groundwater. Water Resour 34(2):140–152

Kowalski AS, Anthoni PM, Vong RJ, Delany AC, Maclean GD (1997) Deployment and evaluation of a system for ground-based measurement of cloud liquid water turbulent fluxes. J Atmos Ocean Technol 14(3):468–479

Lázaro R, Rodrigo FS, Gutiérrez L, Domingo F, Puigdefábregas J (2001) Analysis of a 30-year rainfall record (1967–1997) in semi-arid SE Spain for implications on vegetation. J Arid Environ 48:373–395

Lerner DN, Issar AS, Simmers I (1990) Groundwater recharge. A guide to understanding and estimating natural recharge. IAH International Contributions to Hydrogeology, vol 8, Heise. Hannover

Li XY, Contreras S, Solé-Benet A (2008) Unsaturated hydraulic conductivity in limestone dolines: influence of vegetation and rock fragments. Geoderma 145:288–294

Maréchal JC, Varma MRR, Riotte J, Vouillamoz JM, Kumar MSM, Ruiz L, Sekhar M, Braun JJ (2009) Indirect and direct recharges in a tropical forested watershed: Mule Hole, India. J Hydrol 364:272–284

Marín-Lechado C, Galindo-Zaldívar J, Rodríguez-Fernández LR, González-Lodeiro F (2005) Structure of the Campo de Dalías from gravimetric and seismic data. Faulted hybrid joints: an example from the Campo de Dalias (Betic Cordilleras, Spain). J Struct Geol 26:2025–2037

Martin-Rojas I, Somma R, Delgado F, Estévez A, Iannace I, Perrone V, Zamparelli V (2009) Triassic continental rifting of Pangaea: direct evidence from the Alpujarride carbonates, Betic Cordillera, SE Spain. J Geol Soc 166:447–458

Martín-Rosales W, Gisbert J, Pulido-Bosch A, Vallejos Á, Fernández-Cortés Á (2007) Estimating groundwater recharge induced by engineering systems in a semiarid area (southeastern Spain). Environ Geol 52:985–995

Oyonarte C, Escoriza I, Delgado R, Pinto V, Delgado G (1998) Water-retention capacity in fine earth and gravel fractions of semiarid mediterranean montane soils. Arid Soil Res Rehabil 12:29–45

Pulido-Bosch A, Pulido-Lebouf P, Molina L, Vallejos A, Martín-Rosales W (2000) Intensive agriculture, wetlands, quarries and water management. A case study (Campo de Dalías, SE Spain). Environ Geol 40(1–2):163–168

Ross M, Geurink J, Said A, Aly A, Tara P (2001) Evapotranspiration conceptualization in the HSPF-MODFLOW integrated models. J Am Water Resour Assoc 41:1013–1025

Rushton KR, Eilers VHM, Carter RC (2006) Improved soil moisture balance methodology for recharge estimation. J Hydrol 318:379–399

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds M, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20(15):3335–3370

Serrano-Ortiz P, Domingo F, Cazorla A, Were A, Cuezva S, Villagarcía L, Alados-Arboledas L, Kowalski AS (2009) Interannual CO_2 exchange of a sparse Mediterranean shrubland on a carbonaceous substrate. J Geophys Res 114:G04015. doi:10.1029/2009JG000983

Simmers I, Hendrickx JMH, Kruseman GP, Rushton KR (1997) Recharge of phreatic aquifers in (semi)arid areas. International Contributions to Hydrogeology 19. IAH, Balkema, Rotterdam

Sorman AU, Abdulrazzak MJ, Morel-Seytoux HJ (1997) Groundwater recharge estimation from ephemeral streams. Case study: Wadi Tabalah, Saudi Arabia. Hydrol Process 11:1607–1619

Summer G, Homar V, Ramis C (2000) Precipitation seasonality in eastern and southern coastal Spain. Int J Climatol 21:219–247

Vallejos A, Pulido-Bosch A, Martín-Rosales W, Calvache ML (1997) Contribution of environmental isotopes to the knowledge of complex hydrologic systems. A case study: Sierra de Gador (SE Spain). Earth Surface Proc Landforms 22:1157–1168

Vandenschrick G, van Wesemael B, Frot E, Pulido-Bosch A, Molina L, Stievenard M, Souchez R (2002) Using stable isotope analysis (δD-δ^{18}O) to characterise the regional hydrology of the Sierra de Gádor, south east Spain. J Hydrol 265:43–55

Verma SB, Baldocchi DD, Anderson DE, Matt DR, Clement RE (1986) Eddy fluxes of CO_2, water vapour and sensible heat over a deciduous forest. Boundary Layer Meteorol 36:71–91

Vidal S (1994) Sensor for simultaneous moisture and electric conductivity measurement in soils. Spain, Patent 9401681

Wood WW, Sanford WE (1995) Chemical and isotopic methods for quantifying ground-water recharge in a regional, semi-arid environment. Ground Water 33(3):458–468

Wood WW, Rainwater KA, Thompson DB (1997) Quantifying macropore recharge: examples from a semi-arid area. Ground Water 35(6):1097–1106