

Groundwater recharge in semi-arid carbonate aquifers under intensive use: the Estepa Range aquifers (Seville, southern Spain)

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Abstract Quantifying groundwater recharge in carbonate aquifers located in semi-arid regions and subjected to intensive groundwater use is no easy task. One reason is that there are very few available methods suitable for application under such climatic conditions, and moreover, some of the methods that might be applied were originally designed with reference to non-carbonate aquifers. In addition, it is necessary to take into account the fact that, in any given aquifer, groundwater recharge is modified by the groundwater exploitation. Here we focus on four methods selected to assess their suitability for estimating groundwater recharge in carbonate aquifers affected by intensive exploitation. The methods were applied to the Estepa Range aquifers of Seville, southern Spain, which are subjected to different degrees of exploitation. Two conventional methods were used: chloride mass balance and daily soil–water balance. These results were compared with the results obtained by means of two non-conventional methods, designed for application to the carbonate aquifers of southern Spain: the APLIS and ERAS methods. The results of the different methods are analogous, comparable to those obtained in nearby non-exploited carbonate aquifers,

confirming their suitability for use with carbonate aquifers in either natural or exploited regimes in a semi-arid climate.

Keywords Water resources · Hydrogeology · Aquifers management · Renewable resources · Karst · Spain

Introduction

The satisfactory management of groundwater in arid and semi-arid areas must be based on previous evaluation of aquifer recharge (Kinzelbach et al. 2002; Scanlon et al. 2006). In these regions, where groundwater is the major source of water, aquifers are subjected to intermittent recharge episodes (Foster et al. 1982). Carbonate aquifers present particular hydrogeological attributes, such as a high infiltration rate, high water storage capacity, and adequate water quality for different uses. Such characteristics reveal the high strategic interest of these aquifers, which may very well gain in importance and prominence in the near future, making it necessary to implement scientific-based strategies to manage these water resources.

Traditionally, the recharge of non-exploited carbonate aquifers has been estimated using water balance methods. These assume that the average annual discharge value is equal to the average annual recharge, considering a long-term behavior and equivalent hydrodynamic conditions (Bredenkamp and Xu 2003). However, aquifer recharge is often directly modified by groundwater water pumping (Bredhoeft et al. 1982) and by induced land use changes (Scanlon et al. 2006). Most of the methods used to quantify recharge were furthermore developed for use in detrital aquifers, and therefore do not consider the different and complex behavior of carbonate aquifers, which are

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characterized by heterogeneous porosity and permeability (Ahr et al. 2005; White 1999; Worthington 1999). Both features, porosity and permeability, have an impact on (1) infiltration (diffuse and/or concentrated), (2) flow along the unsaturated zone (matrix, fractures and the karstic conduit network), and (3) discharge (diffuse and/or concentrated) (Bakalowicz 2005; Kiraly 2003).

Several authors have described the different techniques and more suitable conditions for evaluating groundwater recharge (Lerner et al. 1990; Scanlon et al. 2002; Zhang and Walker 1998). Some papers focus on the groundwater recharge occurring in arid and semi-arid zones (Bhuiyan et al. 2009; Dassi 2010; Hendrickx and Walker 1997; Kalantari et al. 2009; Kinzelbach et al. 2002; Scanlon et al. 2006; Yangui et al. 2011). However, none of these methods can be used in all situations, and each has specific problems. In addition, it is well known that groundwater recharge has a large temporal and spatial variability. This fact a high uncertainty degree during its evaluation (Custodio 1997; Custodio et al. 1997; de Vries and Simmers 2002; Flint et al. 2002; Scanlon et al. 2002, 2006), even when the only source of groundwater recharge is rainwater. To minimize the degree of uncertainty, different methods are usually compared to establish a groundwater recharge range with an associated uncertainty value (Healy and Cook 2002; Nimmo et al. 2003; Risser et al. 2009; Scanlon et al. 2002). This approach yields a good approximation to the real recharge value, yet there are usually not enough data to properly apply several methods (Risser et al. 2009).

In the past, groundwater resources have not been adequately managed in Spain (Custodio et al. 2009; Llamas and Martinez-Santos 2005) leading to the intensive groundwater use of several carbonate aquifers located in the south of the country (Llamas and Custodio 2003). The river basin management staff tends to turn to hydrogeologists when the problems of intensive exploitation appear. The intensive exploitation of these aquifers, their small size (<100 km²), their high hydraulic diffusivity (T/S), and the large dry periods occurring between groundwater recharge events, cause a fast drop in their groundwater level and frequent desiccation of springs. All of these facts make difficult the proper evaluation and study of these aquifers. Estimating groundwater recharge, which can be easily and precisely evaluated in natural conditions by monitoring the water discharge points, can thus become a complex task.

The aim of this paper is to evaluate the groundwater recharge of the semi-arid carbonate aquifers pertaining to the Estepa Range (southern Spain) using four independent methods. The studied aquifers present a range in the degree of exploitation, from natural conditions to intensive exploitation. This allowed us to assess the suitability of the four selected methods in estimating the recharge in semi-arid carbonate aquifers and to appraise the influence of the

different degrees of exploitation. We used two conventional methods: the Chloride Mass Balance (CMB) (Eriksson and Khunakasem 1969) and daily soil–water balance (SWB) (Milly 1994a, b), and two methods designed for application to the carbonate aquifers of southern Spain: the APLIS (Andreo et al. 2008) and ERAS methods (Murillo and de la Orden Gómez 1996). The available data and conceptual model of recharge that make this analysis possible could, in view of the obtained results, prove useful for the future management of other carbonate aquifers in semi-arid regions.

Study area

The Estepa Range is located in the western Betic Cordillera (southern Spain), 120 km east of the city of Seville (Fig. 1). This range is a small carbonate massif formed by outcrops of Jurassic limestone and dolostone that constitute several aquifers subjected to differing degrees of exploitation. Although the total exposed permeable surface is relatively small (34 km²) and is distributed over five independent aquifers (Martos-Rosillo 2008), they supply water to some 36,000 people as well as around 600 ha of irrigated land (IGME 2006a).

Geological setting

The studied aquifers belong to the Subbetic Domain of the Betic Cordillera (Fig. 1).

The Subbetic sequence contains Mesozoic to Early Miocene rocks. During Triassic times, deposition was dominated by continental clastic sedimentation sandstones, claystones, and gypsiferous claystones. A transgressive shallow-marine limestone platform formed during the Early Jurassic. The Jurassic limestone sequences constituted isolated ranges of variable size, which are surrounded by Triassic clays and Cretaceous to Miocene marls. This geological setting affects the hydrogeological behaviour of the carbonate aquifers developed in the Subbetic Zone. They are generally small aquifers (<100 km²), highly deformed and bounded by low permeable rocks at the base and boundaries.

Meteorological data, soil and vegetation

Average precipitation during the studied period (1976–2006) and its associated SD are 500 ± 150 mm/year. Analysis of precipitation time variability reveals high inter-annual heterogeneity. Three drought events occurred during the analyzed period (1983–1986, 1990–1995 and 2004–2006). This fact directly affects the groundwater recharge because precipitation is characterized by brief but heavy rainy periods that alternate with lengthy dry periods.

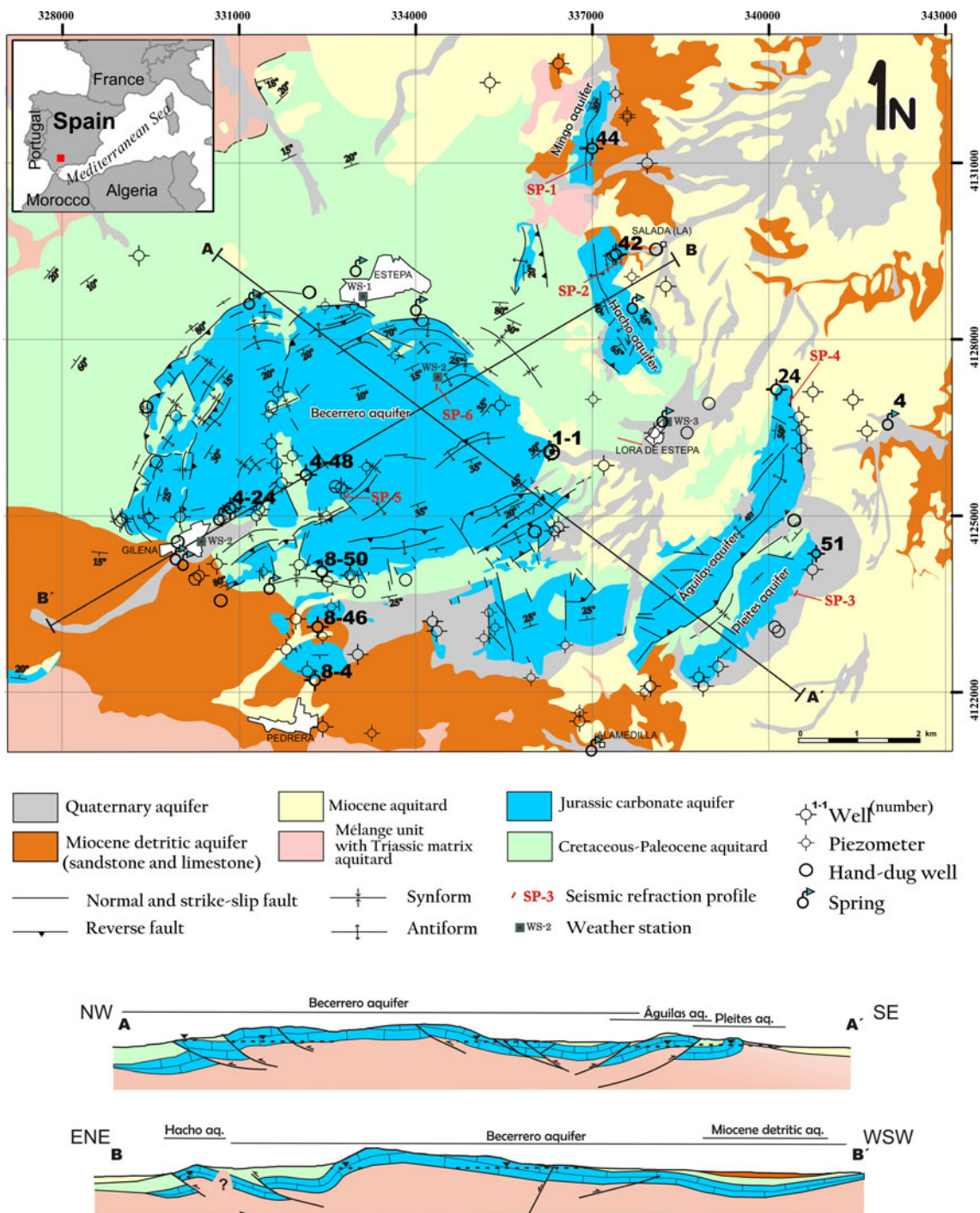


Fig. 1 Geographical location and geological setting. Weather Station (WS) and borehole placement are shown. *Dashed line* shows the position of the water table in each aquifer

Rainy days average around 60 per year, and just a few days may contain the bulk of annual precipitation. The recorded average annual number of days exceeding rain intensities of 2, 10, and 20 mm/day are, respectively, 45, 18, and 6 days.

The annual average for evapotranspiration in the studied period (1976–2006) obtained from the nearby meteorological

stations was between 1,193 and 1,300 mm/year. The annual ratio of precipitation to potential evapotranspiration was between 0.38 and 0.42, making it a semi-arid climatic region, following the UNESCO criterion (UNESCO 1979).

Mainly two types of soils dominate the edaphic cover of the region: thin lithosols that support scrubland and a dense vegetal cover which are mainly developed on convex

hillsides and mountaintops; and well developed soils in zones with a low slope. In the lithosols, the total available soil water (w_0) in the root zone (TAW)—which is the difference between the water content at field capacity and wilting point (Allen et al. 1998)—is between 20 and 40 mm (Martos-Rosillo 2008), which is similar to the values obtained in soil above the carbonate aquifers of southern Spain (Oyonarte et al. 1998). In well-developed soils, including chromic luvisols placed in concave and flat hillsides, a greater vegetal cover of scrubland and conifer trees is normally found. The role of this vegetation during the groundwater recharge process is important; although there is limited water retention (Domingo et al. 1998; Llorens 1997), root extraction is very significant. Thus, in the Gador range (Almeria), also in the south of Spain, very similar vegetal communities installed above the same soils produce annual evapotranspiration rates (actual evapotranspiration/precipitation) of 0.65 ± 0.12 (Contreras et al. 2008).

Geomorphology

The studied aquifers present an early state of karstification that is characterized by the development of karrens, limestone pavements and few dolines (Fig. 2). There are no endokarstic formations described. The tops of the ranges are sectors with low slope that are dominated by karrens, favouring rainwater infiltration, and an almost total absence of surface water runoff (Fig. 3). The occasional surface and subsurface runoff water is infiltrated along the boundaries of the carbonate massifs at the base of the hillsides. We stress the absence of rivers flowing over the carbonate massifs. Within the studied area, the thickness of the unsaturated zone was determined by means of a refraction seismic survey (IGME 2006b) performed along the sectors where the groundwater recharge mainly occurs. Three profile types can be distinguished (Fig. 4). The first type (SP-4) presents a thin alteration zone (0.4–3.3 m depth) and occurs along the sectors with a high slope gradient, such as the hillsides. The second type (SP-6) is associated with the low slope sector situated atop the ranges, and has alternating zones of variable thickness, between 0 and 6.5 m, and an irregular contact surface with the unaltered limestone. The third profile (SP-3) occurs at the base of the hillsides, in the sectors where the slope decreases. Three layers characterize it. The shallowest layer has an average thickness of 0.8 m and velocity coinciding with that of a lithosol associated with the limestone alteration. The seismic velocity in the intermediate layer suggests the presence of altered limestone with a thickness of 1.3–7.7 m, corresponding to the epikarst zone. The deepest layer corresponds to the limestone bedrock. It is necessary to point out that the contact between the epikarst and the bedrock limestone layer has an

irregular morphology, as seen in the SP-4 profile. This morphology suggests that a doline formation process is just starting, following the model of Williams (Williams 1983).

Hydrogeology

Two independent sectors with different hydrogeological behaviour are recognized in the Estepa Range (Fig. 1): the Estepa Sector (ES), containing the Becerrero aquifer; and the Hacho-Mingo-Guinchon Sector (HMGS), formed by the Mingo, Hacho, Aguilas, and Pleites aquifers. All these carbonate units are surrounded by the so called Antequera-Osuna nappe (Cruz-Sanjulián 1974), which is mainly composed by silts, marls, and evaporites of Triassic age. In addition, Cretaceous-Paleogene marls and marly limestone units are present in disperse outcrops. Unconformably placed above the Mesozoic sequences, marly Neocene and detrital Quaternary sedimentary rocks crop out.

The Jurassic rocks of the Becerrero aquifer consist of a 400 m (average) thick carbonate sequence developed above a Triassic clay-in-matrix tectonic mélangé, and locally overthrust by the Cretaceous units. The Jurassic permeable carbonates crop out over 26.2 km². The boundaries of the carbonate units are barriers to groundwater flow. The values of effective porosity are reported to be between 1.5 and 3.1 % (Ortiz et al. 1995) and coincide with average porosity deduced from the piezometric rise occurring during recharge episodes (Martos-Rosillo 2008).

The hydraulic properties of the aquifers were deduced from aquifer response during eight pumping tests. During constant pumping, the dynamic levels around observation wells progressed following the Hantush model (Hantush and Jacob 1955) induced by water supply from the rock matrix (Martos-Rosillo 2008). Moreover, the imaging and full-wave sonic logs, performed along three boreholes in the central part of the Becerrero Range (Martos-Rosillo et al. 2006), do not cross-cut large karstic cavities. However, this situation is common due to the low probability of cutting the karstic channel network with a few isolated boreholes (Worthington and Ford 1997). The available transmissivity values fit a lognormal distribution, with an average of 120 m²/day, and values ranging from 8 to 1,620 m²/day. Around 6 hm³/year rain-water infiltrates into the aquifer. The total aquifer discharge is 4.6, 3.7 hm³/year of which is used to satisfy the water demands of the population (Lamban et al. 2011; Martos-Rosillo 2008). Under normal conditions, the groundwater flow should advance along the karstic network toward the south to the Ojo de Gilena (4-24), the Ojo de Pedrera (8-4) and the Fuente de Santiago (1-1) springs, at an altitude between 466 and 467 m.a.s.l (Fig. 1).

At present, the most important pumping sectors are grouped around these springs. Therefore, the flow toward

Fig. 2 Geomorphologic scheme of Estepa Range

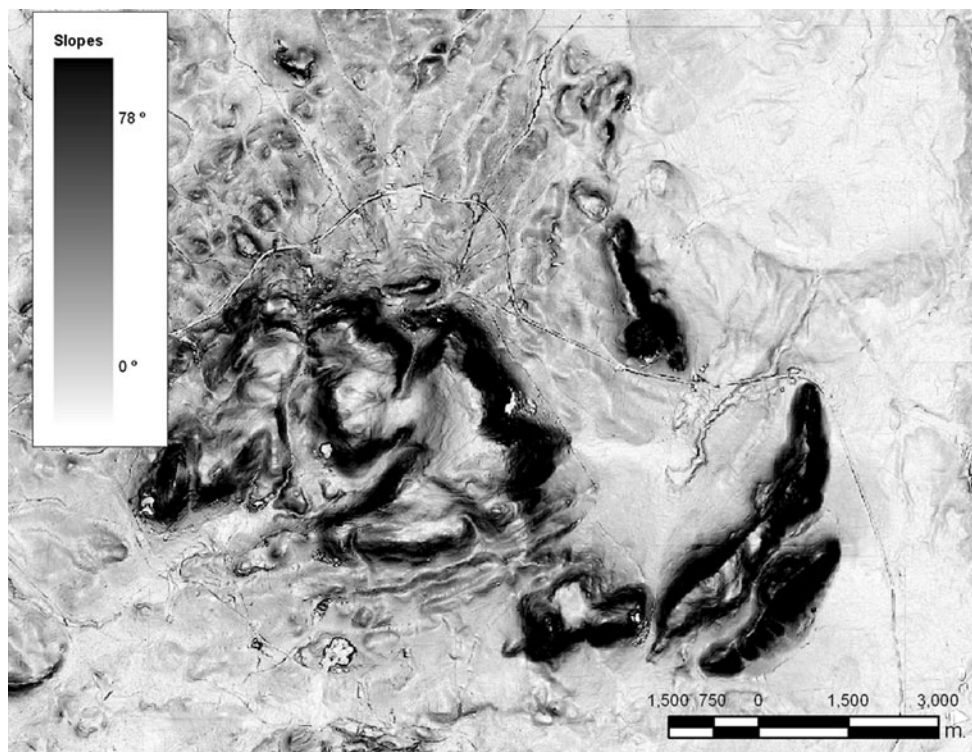
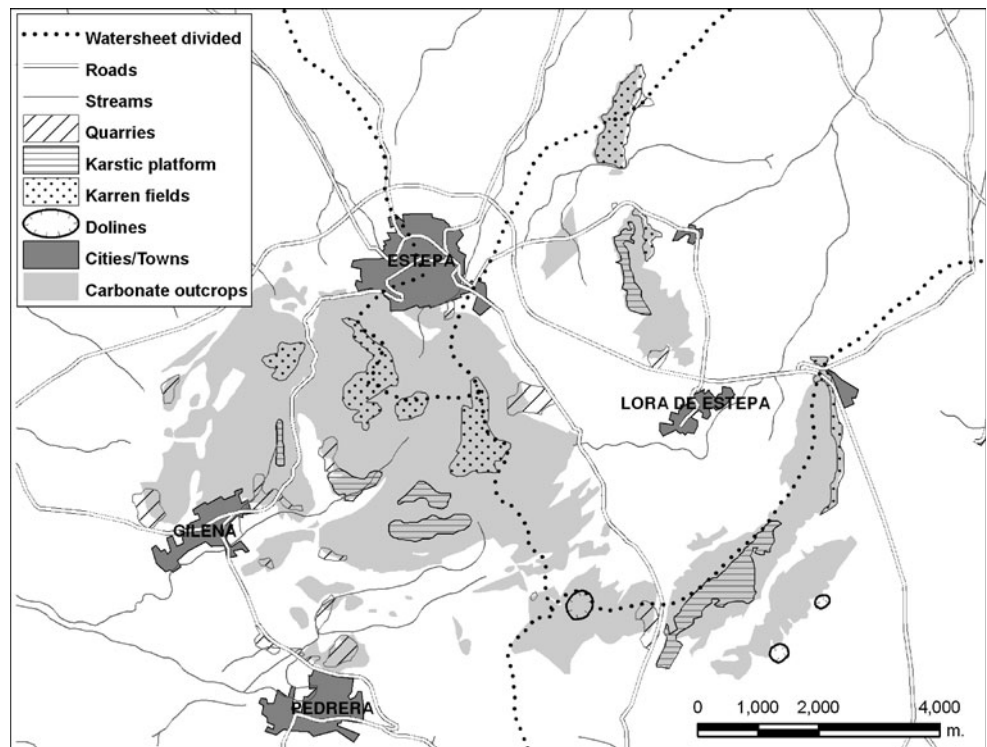
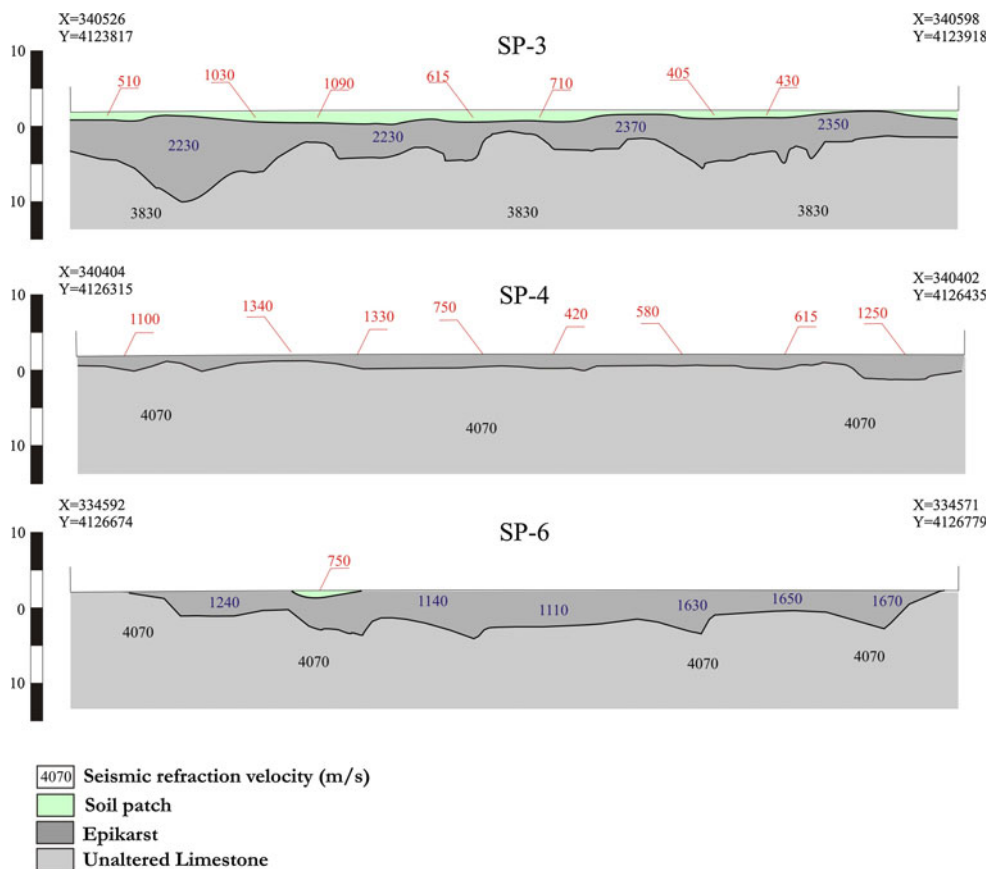


Fig. 3 Slope (%) map of Estepa Range

the boreholes occurs along the intercepted fractures, meaning that the natural direction of groundwater circulation has not changed. Available piezometric data indicate

that the groundwater level response after precipitation is fast (Fig. 5). The intensive exploitation of the aquifer and the prolonged dry period induced accumulative piezometric

Fig. 4 Seismic refraction profiles in flat areas with karren field development (SP-3 and SP-6) and in the break of the slope (SP-4). Horizontal scale 1:1,000

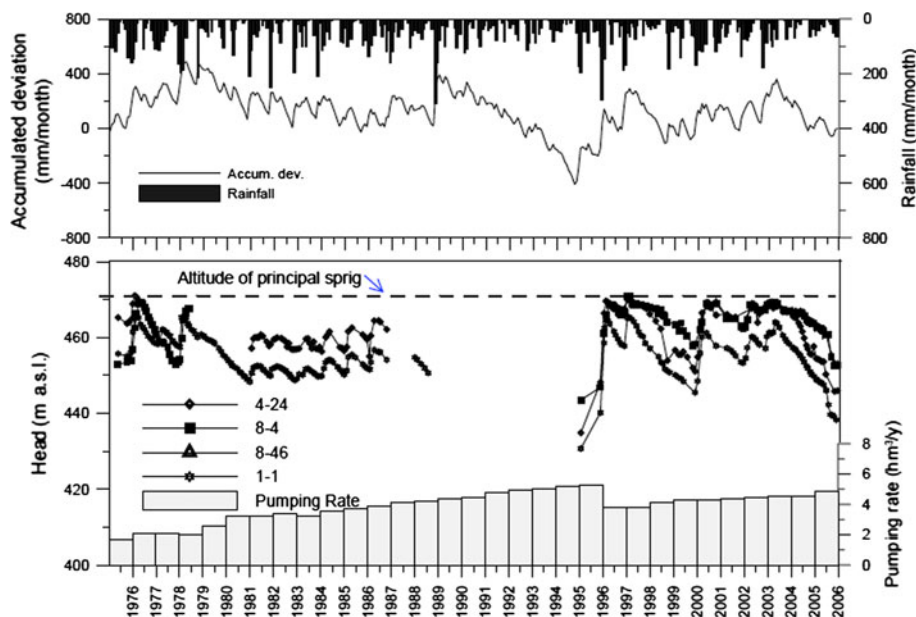


head decline of more than 20 m below the springs' elevations in some periods. After intense rainy periods, the piezometric levels recover and the springs flow again. During the study period (2003–2006), the Ojo de Gilena spring (4-24) was only active during May and July of 2003, and then again between January and October of 2004, whereas the

Fuente de Santiago spring (1-1) was active from April to June 2004.

The permeable Jurassic outcrops in the SHMG aquifer stretch along 8.6 km². Four independent carbonate aquifers have been recognized. The carbonate outcrops along the Hacho and Mingo aquifers extend, respectively, 1.6

Fig. 5 Evolution of the piezometric levels and pumping rates, and comparison with precipitation in the Becerrero aquifer



and 0.6 km² (Martos-Rosillo et al. 2009). The average thickness of the carbonate unit is around 200 m. Both aquifers are highly deformed by NE-SW high-dipping angle normal and strike-slip faults. In the eastern part, the impermeable substrate is formed by silts, marls, and evaporites which are covered by Miocene and Quaternary detrital rocks. Cretaceous marls crop out on the western side of the aquifer.

The Aguilas Range consists of a curved fold-and-thrust nappe. The low permeable Triassic clay-in-matrix tectonic unit is thrust over the Cretaceous sequence that crops out along the core of the Pleites synform, producing the hydrogeological disconnection between the Aguilas and Pleites aquifers.

In the Aguilas aquifer, the permeable carbonate rocks have an average thickness of 350 m and their outcrops cover 4.4 km². Impermeable rocks enclose all its boundaries. Finally, unconformably overlying the Pleites aquifer there are 1.5 km² of carbonate Jurassic outcrops and 0.9 km² of permeable Quaternary rocks. The average thickness of the Jurassic carbonates is 300 m, while the Quaternary detrital sediments reach a maximum thickness of 30 m. All the Pleites aquifer boundaries are barriers to groundwater flow. The time variation of the piezometric level reveals an effective porosity comprised between 0.025 and 0.03 in the water level fluctuation zone of the four aquifers, which is similar to that obtained in the Becerrero aquifer. The reinterpretation of the pumping tests also reveals that the best fit coincides with the Hantush solution. Moreover, almost all the pumping tests show storage effect most likely related to the presence of karstic cavities (Martos-Rosillo 2008). A greater degree of karstification and more abundant fractures than in the Becerrero aquifer contribute to the higher average transmissivity value of 467 m²/day (Martos-Rosillo 2008). The recharge of these aquifers mainly comes from rainwater infiltration. In natural conditions, the groundwater flows to the east, toward the Miocene and Quaternary rocks. The main natural discharge point of the Aguilas aquifer was the Almarjal spring (4), located 335 m.a.s.l. The spring has been inactive since 1995. At present, the significant exploitation of these aquifers induces behavior similar to that of a dammed deposit, where recharge takes place through rainwater infiltration and discharge through pumping. Therefore, the piezometric fluctuation depends on the hydrological balance of the aquifer, its size, and the average porosity of the sector where the water level fluctuates.

In this case, the abundant piezometric information (Fig. 6) confirms the independent behavior of the aquifers which have different piezometric levels and dissimilar temporal evolutions. The aquifer response to rainwater

infiltration is quick in all the aquifers. But again, the effect of water pumping is important. Water exploitation in the Aguilas and Mingo aquifers has caused their heads to decline below the spring discharge elevation. In the Aguilas aquifer, the pumping flow is 1.8 hm³/year, with a recharge of 1 hm³/year. In the Mingo aquifer, pumping flow is 0.28 hm³/year and the infiltration rate is 0.16 hm³/year. Such exploitation deteriorates water quality. A similar imbalance was seen in the Hacho aquifer (with 0.33 hm³/year pumped as opposed to recharge of 0.30 hm³/year), leading to a progressive reduction of the quality of the water and limiting exploitation of groundwater for irrigation due to the risk of soil salinization in the near future (Martos-Rosillo et al. 2009).

Conceptual model of recharge

We propose a conceptual model of recharge based on a deep rainwater infiltration process (Fig. 7). Geometric and structural features limit the lateral transference between aquifers. There are no rivers flowing above the permeable rocks, therefore, the climatic conditions critically control the recharge. Most of the high intensity rain showers occur in November and December and, in a short period of time, there is a fast piezometric level rise in the aquifer. If the intensity of the rainfall is equivalent to the daily potential evapotranspiration (3.4 ± 2 mm), however, there is retention in the vegetation-soil-epikarst system and the water returns to the atmosphere via evapotranspiration. We should therefore emphasize that approximately half of the average annual rainfall in the studied sector—about 250 mm/year—reaches the zone with precipitation intensity higher than 10 mm/day. The absence of karstic formations above the carbonates favouring deep-water infiltration, the maturity of the epikarst, soil expansion, the abundant vegetated sectors, and the presence of large flat sectors at the top of the ranges would all enhance direct rainwater recharge over the soil matrix and the epikarst. Therefore, in the Estepa Range, the recharge via the karstics outcrops is much more important than the occasional indirect recharge via the Quaternary alluvial deposits located on the hillsides and across discontinuities (fractures, bedding surfaces...). Having crossed the vegetation-soil-epikarst system, the incipient dolinization process, revealed by refraction seismic profiles and seen in some quarries, favours a fast water transition toward the saturated zone across vertical karstic pipes (Fig. 7). The fast groundwater level response after heavy rainfall periods (Figs. 5 and 6) and the hydrogeochemical results confirm this conceptual model of recharge.

Fig. 6 Evolution of the piezometric levels and comparison with precipitation in the Hacho, Mingo, Lora and Aguilas aquifers

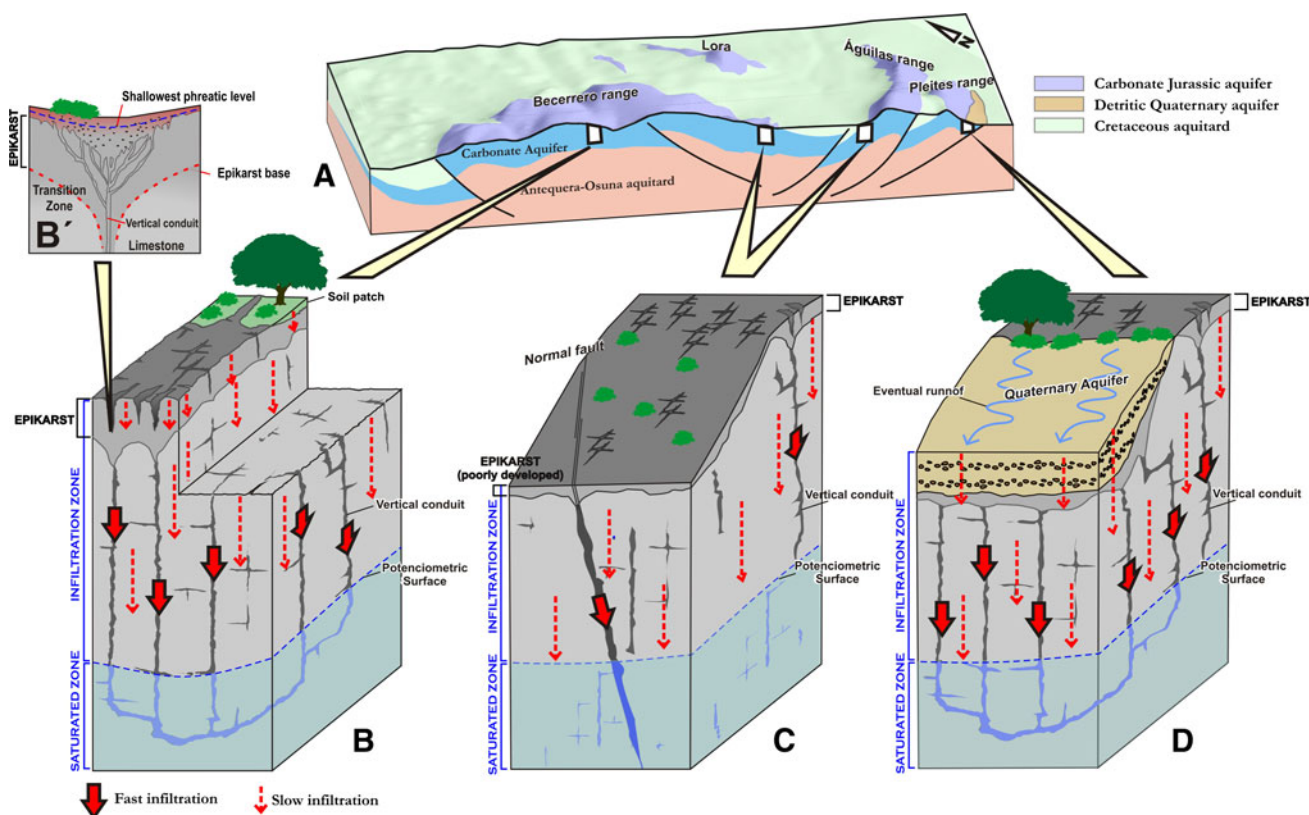
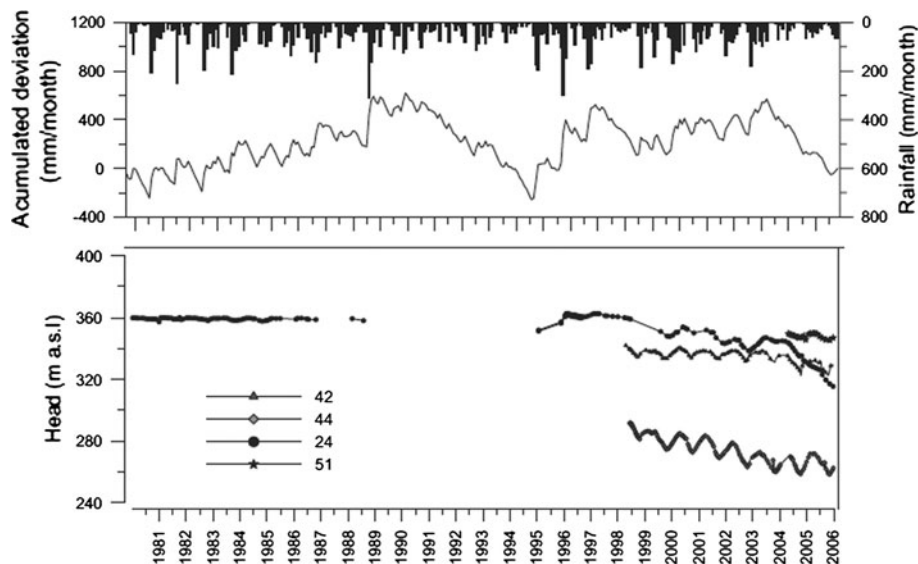


Fig. 7 Conceptual model of recharge processes in Estepa Range. **a** 3D geological scheme of the Estepa Range; **b** Flat areas with karren field development; **c** Break of the slope; **d** areas with overlapping Quaternary materials

Methodology

The methodology used for the different balances is detailed below. First, we discuss the model by Milly (Milly 1994a, b) of soil water balance (SWB). Then, we describe two methods developed specifically to estimate recharge in semi-arid areas: the ERAS (Murillo and

de la Orden Gómez 1996) and APLIS methods (Andreo et al. 2008). Finally, we discuss the main features of the chloride mass balance method (CMB), specifically developed for the estimation of groundwater recharge in carbonate aquifers, isolated from any source of salts apart from rainfall (Eriksson and Khunakasem 1969).

Daily SWB with the Milly model

Milly (1994a, b) analyzed annual SWB using a simple model with limited water storage and an infinite infiltration capacity. The considered soil volume was bounded above by the soil surface and had a depth of 1 m, which is an approximation of the average plant root depth. Milly (1994a, b) further assumed that the horizontal dimension of the considered volume was larger than the horizontal water flow in the root zone, because of soil heterogeneity and local topography (approximately 100 m). The water balance of this volume can be expressed as:

$$\frac{dw}{dt} = p - e - q$$

where p ($l\ t^{-1}$) is the precipitation rate, e ($l\ t^{-1}$) is the actual evapotranspiration rate, and q ($l\ t^{-1}$) is the total discharge rate. A complete description of these assumptions can be found in Milly (1994b). Using these assumptions allows us to express the equation as:

$$\frac{dw}{dt} = \begin{cases} 0 & \text{If } p_i > et_0 \text{ and } w = w_0 \\ 0 & \text{If } p_i < et_0 \text{ and } w = 0 \\ p - et_0 & \text{otherwise} \end{cases}$$

where et_0 ($l\ t^{-1}$) is the reference crop evapotranspiration rate. Moreover, e and q are simply obtained from:

$$e = \begin{cases} et_0 & \text{when } w > 0 \\ 0 & \text{when } w_0 = 0 \end{cases}$$

and

$$q = \begin{cases} 0 & \text{when } w < w_0 \\ p - et_0 & \text{when } w = w_0 \text{ and } p > et_0 \end{cases}$$

We used this model in our study assuming a daily time-step, driven with complete meteorological data from several meteorological stations within the Estepa Range.

APLIS method

This method allows for the determination of average annual recharge in carbonate aquifers as a percentage of precipitation, based on the following variables: Altitude (A), Slope (P), Lithology (L), Infiltration landforms (I) and Soil (S), using the following expression (Andreo et al. 2008):

$$R = (A + P + 3 \cdot L + 2 \cdot I + S)/0.9$$

Ten categories were specified for each variable, such that each corresponded to a score ranging from 1 to 10, following an arithmetic progression; thus, they could be straightforwardly compared with the percentage values of recharge. A value of 1 represents minimal coincidence with aquifer recharge, and a value of 10 expresses maximum influence on recharge.

The values for altitude were separated into classes with one-by-one arithmetic progression, so that the higher the altitude, the greater the precipitation and the greater the aquifer recharge. The altitude values were grouped into intervals of 300 m. Above an altitude of 2,700 m a.s.l., differences in recharge were insignificant. The scores assigned to the slope parameter decreased by one unit with increasing slope, so that the greater the slope, the lower the recharge into the aquifer.

Scores were allocated to the diverse types of lithology on the basis of hydrogeological criteria. As the APLIS method is mainly intended for estimating the recharge into carbonate aquifers, scores of 5–10 were attributed, depending on the degree of karstification. Accordingly, the higher the degree of karstification, the higher the recharge into the aquifer. Two scores were assigned to the variable reflecting the zones of preferential infiltration: a value of 10 for zones where there were areas of preferential infiltration, and a value of 1 in the rest of the cases. From aerial photographs and field surveys it is relatively simple to classify areas where preferential infiltration features predominate. In the case of soil types, the different classes were grouped depending on the general characteristics of predominant thickness and texture. Thus, in soils that are not highly evolved, as is the case of lithosols, where the soil coverage is generally scant and the texture very coarse, recharge values are maximum (a score of 10 is given); on the other hand, where soils are thick and clayey (vertisols), recharge is minimal (and a score of 1 is used).

By dividing the expression by 0.9, there is always some degree of recharge, but it never reaches 100 % of the precipitation. The mean value of the recharge rate (R) in each aquifer was obtained as the mean of the values of R corresponding to each of the spatial units in the recharge map. The mean rate of annual recharge represented was grouped into five regular intervals, each assigned a recharge class: very low, low, moderate, high, or very high (Andreo et al. 2008).

ERAS method

ERAS is the Spanish acronym for “Estimating the Recharge in Overexploited Aquifers”. For the ERAS code to be applied correctly, there must be no lateral outputs or springs draining the aquifer, and recharge must take place entirely and exclusively by the direct infiltration of rainfall.

In the ERAS code, natural recharge onto the aquifer (R_i) represents a fraction of the effective rainfall (ER_i), which is determined by the following expression (1):

$$ER_i = (P_i - T_i^\beta) \tag{1}$$

where P_i is the rainfall (m/month) and T_i is the mean air temperature ($^\circ\text{C}$) during month i , and where β is a non-

dimensional calibration parameter, the mean value of which, ascertained by experimentation (Iglesias-López 1984) is 1.4, yet it could range from 1.3 (in cold zones) to 1.6 (in warmer zones). The natural recharge, R_i (m^3/month), to the aquifer during month i is expressed as (2):

$$R_i = M(P_i - T_i^\beta)^N \quad (2)$$

where M and N are non-dimensional parameters of linear and potential correlation, respectively, that are to be calibrated.

The variation in the storage (VS) that takes place during period i is calculated using the following expression (3):

$$VS_i = \Delta h_i FGS = \Delta h_i (A \times S)_i \quad (3)$$

where Δh_i (m) is the variation in the piezometric level and FGS (Factor of Global Storage) is equal to the product of the storage coefficient (S), i.e. effective porosity, and the area (m^2) of the aquifer (A). It should be mentioned that this method could only be applied to unconfined aquifers (i.e. S = effective porosity).

The storage variation (SV) can also be expressed as (4):

$$SV_i = R_i - B_i \quad (4)$$

where B_i (m^3/month) is the volume of water extracted during month i . By combining expressions (3) and (4), one obtains an expression that relates the variables ‘variation in piezometric level’, ‘recharge’ and ‘pumped extraction’, for a given month i :

$$R_i - B_i = \Delta h_i FGS$$

$$\Delta h_i = \left(M(P_i - T_i^\beta)^N - B_i \right) / FGS \quad (5)$$

The analysis periods are identified with each natural month. The input data to the model (precipitation, temperature, pumping volumes and variations in piezometric level) should be used at the same rate (i.e. for monthly intervals). In order to fit the real value of Δh_i to those of the model, it is necessary to iteratively calibrate the values of M , N and S from equation (5) (the latter depends on the lithology of the aquifer).

Chloride mass balance (CMB)

This method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface. It can be used for estimating a moisture flux in the unsaturated zone by means of a profiling technique when diffuse (piston) flow is assumed and for recharge. Comparison of moisture flux and recharge provides insight into the mechanism of recharge. Note that in a broader context, mechanisms of recharge and recharge rates can be considered crucial in the assessment of vulnerability of groundwater resources to pollution.

For a steady state between the chloride flux at the surface and the chloride flux beneath an upper zone where evapotranspiration and mixing of rainfall and pore water takes place, and excluding runoff and run-on, a site specific moisture flux can be calculated for the unsaturated zone by (Eriksson and Khunakasem 1969):

$$R_{sm} = \frac{P \times Cl_p + D}{Cl_{sm}} = \frac{TD}{Cl_{sm}}$$

where R_{sm} is the moisture flux (diffuse or slow flow component; mm/year), P is rainfall (mm/year), Cl_p and Cl_{sm} are chloride concentrations in rainfall and soil moisture (mg/l), and D is dry chloride deposition ($\text{mgm}^{-2}\text{year}^{-1}$). The sum of $P \times Cl_p$ and D is also referred to as ‘‘Total atmospheric chloride Deposition’’ (TD) and originates from both precipitation and dry fall-out.

A better estimate of the moisture flux is obtained from a mass balance, which integrates chloride and moisture contents cumulatively (c) over a specific depth interval:

$$R_{sm(c)} = \frac{TD \times TM}{TC}$$

where TM is total moisture content (mmm^{-2}) and TC is total chloride content (mgm^{-2}). Simply substituting Cl_{sm} in the equation for the chloride concentration in groundwater at the water table (Cl_{gw}) gives a total recharge rate R_T :

$$R_T = \frac{TD}{Cl_{gw}}$$

Cl_{gw} originates from different flow components in the unsaturated zone. For an areal R_T , Cl_{gw} represents the mean of chloride concentrations in groundwater.

Results

Different problems limit the possibility of applying the balance methods to all the studied aquifers. The CMB was applied only in the Becerrero aquifer, due to the presence of chloride from external sources of precipitation in the other aquifers. In turn, the ERAS method was calculated only in the sectors with high quality pumping data (i.e. Hacho, Mingo, and Aguilas aquifers). The APLIS and daily SWB methods were applied in all the aquifers.

Daily SWB (Milly model)

It is necessary to assume a soil water-holding capacity WHC value to apply the SWB. We tried to establish the soil WHC (w_o) by comparing different w_o with the groundwater level variability observed at the points with higher time data density. However, analysis reveals that, in one same aquifer, the time variability of the groundwater

level has a close relationship with calculated daily recharge using a specific w_0 value (Table 1).

APLIS method

The APLIS method allows us to obtain a map with the spatial distribution of the water infiltration rate. This distribution can be observed in Fig. 8. In addition, the combination of the isohyets map (period 1981–2006) and the obtained recharge percentage makes it possible to estimate the annual average volume of water infiltrating each aquifer (Table 2).

ERAS method

We calibrated the parameters M , N , and S of equation (4) by successive iterations in order to minimize the difference between the modelled and measured groundwater levels. In the case of the water storage capacity, most of the carbonate aquifers of the Estepa Range have an average effective porosity between 0.02 and 0.03 (Martos-Rosillo 2005; Ortiz et al. 1994). The calibrated equation (5) applied to the Mingo (6), Hacho de Lora (7), and Aguilas-Guinchon (8) aquifers is:

$$\Delta h_i = \left[1.6 \cdot (P_i - T_i^\beta)^{0.91} - B_i \right] / (A \cdot 0.025) \tag{6}$$

$$\Delta h_i = \left[0.87 \cdot (P_i - T_i^\beta)^{1.01} - B_i \right] / (A \cdot 0.03) \tag{7}$$

$$\Delta h_i = \left[1 \cdot (P_i - T_i^\beta)^{0.96} - B_i \right] / (A \cdot 0.029) \tag{8}$$

The regression lines between modelled and measured groundwater levels provide R^2 values that are always over 0.8 (Fig. 9). The greatest errors of the calibration coincide with the aquifers where the pumping data are inaccurate. After the calibration stage, a sensitivity analysis of each parameter was performed. The three models are very sensitive to variations of the parameter S . When S is beyond the range 0.02–0.03, the groundwater level values tend to be more distant from the real values (Fig. 9). The sensitivity values of the N parameter suggest that the

results are inconsistent with data outside the range 0.95–1.05. In the case of the M parameter, the acceptable values are between one- and two-tenths both above and below the fit values in each model. Using the calibration parameters and the precipitation-temperature data from the nearby weather station (Lora WS), we estimated the groundwater recharge for the period 1981–2006 (Table 3).

Chloride mass balance (CMB)

Table 4 shows the values of recharge (mm/year) obtained using the CMB method. We estimated an average recharge of 208 mm/year, which implies 37.9 % of the precipitation of the considered meteorological observatory (WS-1, Fig. 1).

Comparison of methods

The groundwater recharge values obtained with the different methods are quite similar (Fig. 10), especially if we take into consideration the variable geomorphologic and slope features of the studied aquifers. Thus, the annual average recharge and the recharge coefficients are, respectively, between 183 and 283 mm/year, and between 32 and 53 % of the annual average rainwater.

The greatest infiltration coefficients are obtained in the Mingo aquifer (50 %) and the lowest in the Pleites aquifer (34 %). These results are consistent with field observations. The Mingo aquifer is less hilly and is extensively covered by karstic karren forms that favour infiltration. In contrast, the Pleites aquifer has steep topography and a poorly developed epikarst. The APLIS method provides an intuitive map offering the spatial distribution of the infiltration rate (Fig. 8). It is therefore possible to distinguish the high infiltration sectors, which coincide with the flat sector featuring well-developed exo-karstic forms. In addition, it is possible to determine the different recharge capacity of each aquifer. Using APLIS, we estimate recharge values slightly higher than with the other analyzed methods, which yield similar values. This higher estimate has been reported for other aquifers of southern Spain where the APLIS method has been tested (Andreo et al. 2008).

Table 1 Values of recharge (mm/year) obtained with SWB Milly method (1981–2006 period)

Aquifers (w_0)	Becerrero (40 mm)	Mingo (20 mm)	Hacho (40 mm)	Águilas (20 mm)	Pleites (40 mm)
Average	185	240	183	240	183
SD	149	126	129	126	129
Median	177	225	141	225	141
Min.	0	47	10	47	10
Max.	449	480	427	480	427
Dev. Coef.	0.35	0.47	0.36	0.47	0.36

Fig. 8 Recharge (%) map for the aquifers obtained using the APLIS method

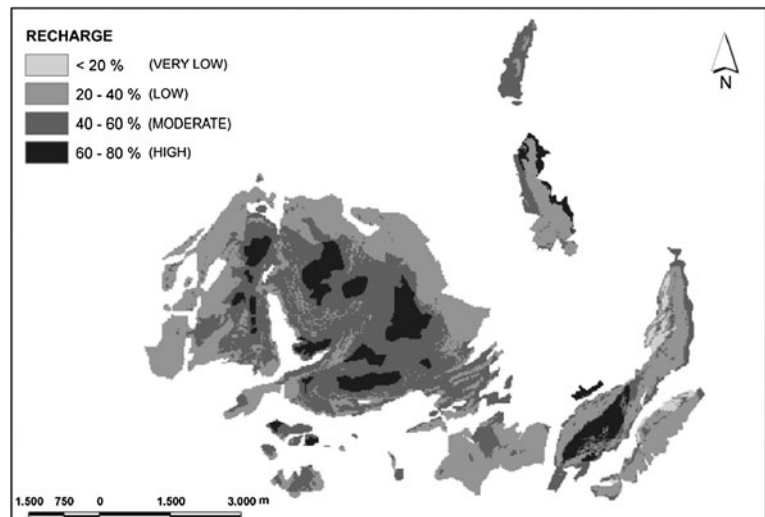


Table 2 Values of recharge (mm/year) and mean recharge rate R (%) obtained with APLIS method

	Becerrero	Mingo	Hacho	Águilas	Pleites
Recharge	246	283	239	237	183
R (%)	0.42	0.53	0.44	0.42	0.32

However, a major drawback of the APLIS method, is its lack of an estimate of the time variability of recharge.

In the Sierra de Becerrero, the SWB and the CMB provide similar results. In addition, the average annual recharge and its variability, determined by the SWB and ERAS methods, coincide in the Mingo, Hacho, and Aguilas aquifers. That is, there is a high correlation between the two methods (Fig. 11). The calculated recharge in the aquifers of the Hacho-Mingo-Guinchón sector is more accurate than that obtained in the Becerrero aquifer, since these coincident results were obtained using independent methods and calibrated with the groundwater level using ERAS.

Discussion

In recent years, there has been a significant increase in the number of papers describing hydrological processes related to carbonate aquifer recharge in arid and semi-arid regions (Alcalá and Custodio 2008; Andreo et al. 2008; Andreu et al. 2011; Bredenkamp and Xu 2003; Mahlknecht et al. 2004; Martínez-Santos and Andreu 2010; Nativ et al. 1995).

In the context of carbonate aquifers located in semi-arid areas in a natural regime, monitoring spring outflow has been considered, to date, the best means of assessing recharge. Yet it can call for long periods of control, given

the high temporal variability of the recharge process. When control of outputs is not necessary or not feasible (e.g., because the outlets have disappeared due to intensive groundwater exploitation), assessment of potential recharge is usually provided through soil water (SWB) and chloride balances (CMB) (Andreu et al. 2011). Even so, no conventional methods for the assessment of potential recharge have been used successfully in southern Spain. This is the background behind the method proposed by Contreras et al. (2008) using a satellite-based eco-hydrological model; or the APLIS method (Andreo et al. 2008), described in this paper.

On the other hand, evaluation methods based on numerical modelling techniques are common in carbonate aquifers subjected to heavy pumping nowadays. Lumped parameter models (e.g., the ERAS model) are being widely applied in semi-arid areas of southern Spain (Aguilera and Murillo 2009; Andreu et al. 2011; Martos-Rosillo et al. 2009). The CRD model is another viable example of this type of model, having been employed in aquifers of South Africa (Beekman and Xu 2003). Noteworthy in this regard is the similarity of results in south-eastern Spain when comparing the lumped and spatially distributed models (Martínez-Santos and Andreu 2010).

Some authors underline considerable differences—as high as 30 %—between the results obtained using models of potential recharge and models that estimate actual recharge (Simmers 1997). According to some authors (Scanlon et al. 2002), in order to reduce uncertainty, such studies should be based on a robust conceptual model of recharge. This was the foremost objective of our research. The choice of methods for assessing recharge was made after an intensive multidisciplinary investigation of meteorological, geological, geomorphological, geophysical, hydrochemical and hydrodynamic aspects, among others.

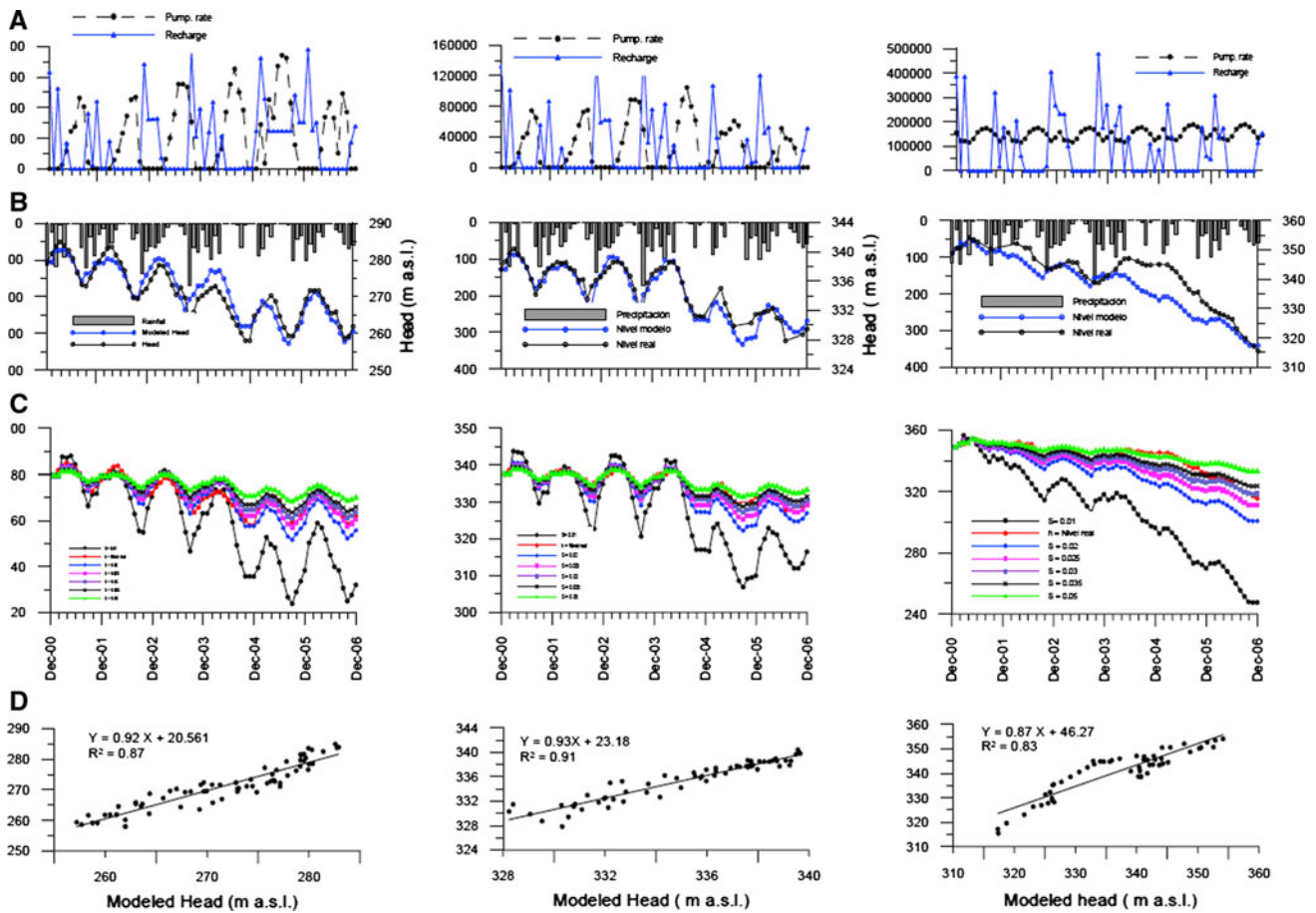


Fig. 9 Results of the modeling after calibration of Mingo (*left*), Lora (*center*) and Aguilas (*right*) carbonate aquifers. Recharge values resulting from the ERAS model and the temporal evolution of the actual head and the modeled head are compared. S: storage coefficient

Table 3 Values of recharge (mm/year) obtained with ERAS method (1981–2006 period)

	Becerrero	Mingo	Hacho	Águilas	Pleites
Average	X	252	188	217	x
SD	X	133	120	106	x
Median	X	204	137	180	x
Min.	X	60	30	57	x
Max.	X	622	529	514	x
Dev Coef.	X	0.49	0.37	0.43	x

Table 4 Values of recharge (mm/year) obtained with CMB method

Station ID	P	C _p	N	C _R	n	R	R (%)
1/1	547.70	4.50	17	10.94	48	225.29	41.13
4/6	547.70	4.50	17	14.58	12	169.04	30.86
4/48	547.70	4.50	17	9.87	8	249.71	45.59
8/50	547.70	4.50	17	13.17	6	187.18	34.18
						Average value	207.81 37.94

P Annual rainfall (mm/year), C_p average chloride content in rainfall (mg/l), C_R average chloride content in groundwater (mg/l), n number of samples, R recharge (mm/year), and R (%) ratio recharge

When considering daily SWB, the coincidence of findings with other methods applied in this paper is not fortuitous. The absence of surface runoff, and the incipient process of karstification in the upper part of the vadose zone of the carbonate aquifers, where abundant patches of vegetation are associated with soils, contribute to making the component of diffuse recharge much more important than the localized, or focused, recharge. Meanwhile, the meteorology of the region indicates that recharge occurs during high-intensity episodes just a few days a year, so

that it is essential to apply the method of SWB on a daily basis, as in the present paper.

The short time of transit of the recharge water through the unsaturated zone of the aquifers—owing to its low thickness and the presence of karst conduits connecting the epikarst to the base of the saturated zone—favours a rapid hydrodynamic response of recharge episodes. Such factors, coupled with the absence of natural outputs, allow for an effective application of the ERAS method.

Fig. 10 Comparisons of estimates of the annual recharge in the Estepa Range aquifers by **a** SWB (Milly), **b** ERAS, **c** CMB and **d** APLIS methods

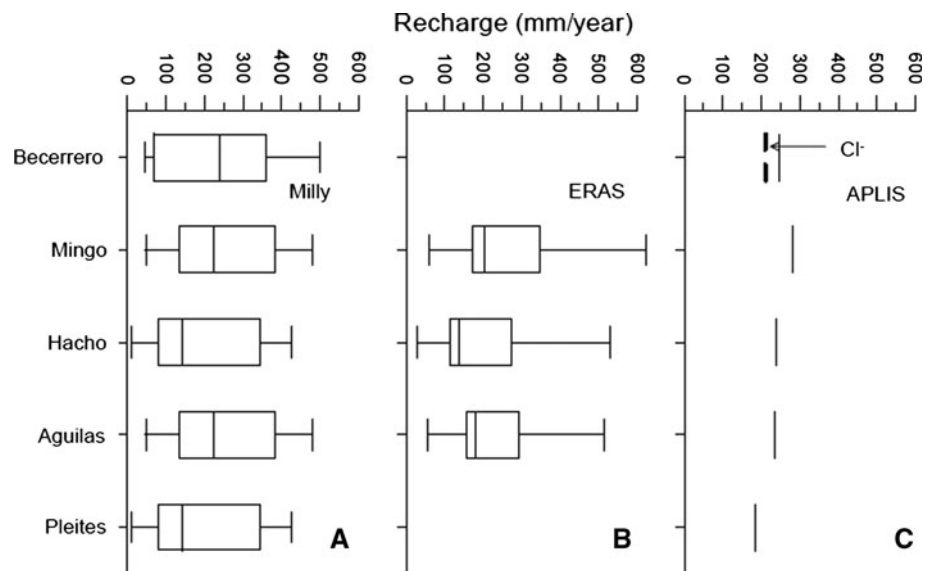
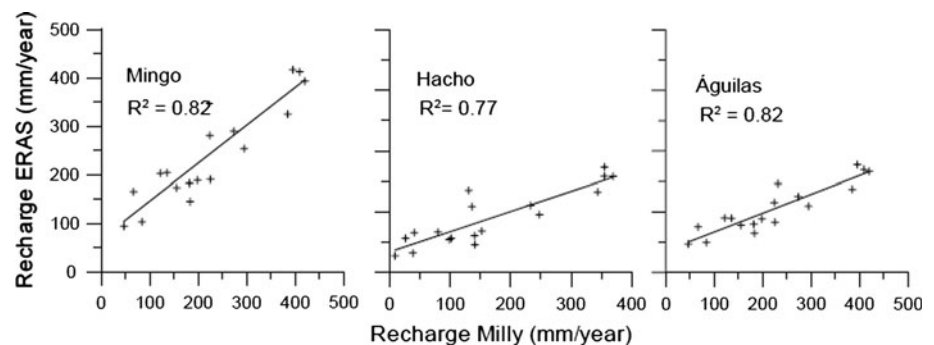


Fig. 11 Scatter plot, showing correlations among estimates of annual recharge with SWB and ERAS methods



The above considerations imply that, in the aquifers of the Estepa Range, minimal differences were seen in the results obtained applying the range of methods for assessing potential recharge (SWB, CMB and APLIS). Furthermore, these results are very similar to the assessment of actual groundwater recharge as estimated by ERAS methodology.

Conclusions

Proper planning for the management of groundwater resources in carbonate aquifers, in areas with arid and semi-arid conditions, requires prior hydrogeological knowledge in natural conditions (i.e. not influenced by pumping). When this is not possible, due to groundwater exploitation, assessment of the recharge is more difficult. The complexity inherent to the characteristics of carbonate aquifers (heterogeneity of porosity and permeability) limits the applicability of methods for assessing recharge. When the springs are severely affected by pumping, assessing the recharge is even more difficult.

The acquisition of the hydrogeological information (e.g., by mechanical borehole drilling) increases the economic costs of research when an aquifer is subject to exploitation. We can therefore affirm that evaluating recharge in aquifers under intensive groundwater use is more uncertain, more difficult and more expensive than in aquifers functioning under a natural regime.

To arrive at a realistic estimation of the recharge rate in over-exploited aquifers, it is necessary to establish the dominant recharge processes and, depending on the other available data, to apply different independent methods and then compare results.

The results of this research study demonstrate that in aquifers with an incipient process of karstification and a rapid piezometric response to precipitation, SWB, CMB and APLIS methods allow a good approximation of the potential recharge. Moreover, the APLIS method can identify the distribution of preferential infiltration areas. The potential recharge obtained was contrasted with an assessment of the actual recharge using the ERAS method. The results are consistent, as the conceptual model of recharge predicted.

To conclude, we should emphasize that the procedure followed in this work, based on establishment of a conceptual model of recharge and contrasting methods for assessing the potential and actual recharge, can be used successfully in other carbonate aquifers in regions with semi-arid conditions. We must add, however, that in order to minimize the uncertainty when assessing recharge, it is necessary to generate accurate information on the daily meteorological data, surface runoff, spring discharge, and changes in groundwater levels, and also to specify the amount and distribution of the exploitation by pumping in the areas of the aquifer.

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