A multi-method approach for groundwater resource assessment in coastal carbonate (karst) aquifers: the case study of Sierra Almijara (southern Spain)

B. Andreo [1] & J. A. Barberá [1] & M. Mudarra [1] & A. I. Marín [1] & J. García-Orellana [2,3] & V. Rodellas [2] & I. Pérez [1]

Abstract Understanding the transference of water resources within hydrogeological systems, particularly in coastal aquifers, in which groundwater discharge may occur through multiple pathways (through springs, into rivers and streams, to- wards the sea, etc.), is crucial for sustainable groundwater use. This research aims to demonstrate the usefulness of the application of conventional recharge assessment methods coupled to isotopic techniques for accurately quantifying the hydrogeological balance and submarine groundwater dis- charge (SGD) from coastal carbonate aquifers. Sierra Almijara (Southern Spain), a carbonate aquifer formed of Triassic marbles, is considered as representative of Mediterranean coastal karst formations. The use of a multi- method approach has permitted the computation of a wide range of groundwater infiltration rates (17–60%) by means of direct application of hydrometeorological methods (Thornthwaite and Kessler) and spatially distributed information (modified APLIS method). A spatially weighted recharge rate of 42% results from the most coherent information on physiographic and hydrogeological characteristics of the studied system. Natural aquifer discharge and groundwater abstraction have been volumetrically quantified, based on flow and water-level data, while the relevance of SGD was estimated from the spatial analysis of salinity, ^{222}Rn and the short-lived radium isotope ^{224}Ra in coastal seawater. The total mean aquifer discharge (44.9–45.9 hm^3 year^{-1}) is in agreement with the average recharged groundwater (44.7 hm^3 year^{-1}), given that the system is volumetrically equilibrated during the study period. Besides the groundwater resources assessment, the methodological aspects of this research may be interesting for groundwater management and protection strategies in coastal areas, particularly karst environments.

Keywords Carbonate rocks · Coastal aquifers · Groundwater resources · Water budget · Spain

Introduction

The hydrogeological balance of aquifer systems is a key issue for groundwater managers, planners and users; however, the evaluation of groundwater resources is not always easy. In fact, historical disagreements on water budget calculations among hydrogeologists are commonly documented in local/ regional studies, which evidence the disparity in the used criteria. In many cases, all components of the water budget equation are accurately quantified, while in some others, individual water volumes are difficult to assess due to the system complexity and unknown components—e.g. groundwater transference between aquifer sectors, submarine groundwater discharge (SGD), etc.

Aquifer recharge has been traditionally estimated from the spatial analysis of available meteorological data. Unlike predominantly flat regions where precipitation patterns vary gradually, rainfall patterns in mountainous areas are often strongly conditioned by altitudinal gradients, resulting in

[1] Department of Geology and Centre of Hydrogeology at the University of Málaga, University of Málaga, Ada Byron Scientific Research Building, Francisco de Peñalosa 18, 29071 Malaga, Spain
[2] CEREGE, Aix-Marseille Université, CNRS, IRD, Coll France, 13545 Aix-en-Provence, France
[3] Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, 08193 Bellaterra, Catalonia, Spain

recharge assessments mainly constrained by spatial data rep- resentation (e.g. a spatially well-distributed meteorological monitoring network). For decades, recharge assessment in hydrogeological systems has been usually performed by ap- plying empirical methods (Thornthwaite 1948; Penman 1948; Turc 1954; Coutagne 1954; among others), the main advan- tage being the reduced number of physical variables that they require (i.e. air temperature, rainfall, solar radiation, etc.); data for these variables are commonly acquired by climate obser- vation programs of public administrations. Individual re- charge components can also be iteratively computed by using automatic mathematical codes such as BALAN (Samper and García Vera 1992), widely applied for water budget estima- tions in the aquifers of Spain and Portugal (Samper and García-Vera 1997; Manzano et al. 1997; Samp er et al. 2007). Meanwhile, the most commonly applied chemical method, the chloride mass balance (CMB) method (Eriksson and Khunakasem 1969), provides average recharge coeffi- cients in a long-term period, because its application is more suitable for regional-scale studies (i.e. aquifer or catchment scale; Alcalá 2006; Martos-Rosillo et al. 2013). However, the existence of Cl^- sources other than meteoric ones (e.g. geogenic source) may invalidate the results of the CMB. Due to the inherent particularities of carbonate aquifers, karst-specific methods for recharge assessment have been de- veloped based on hydrometeorological data (Kessler 1967) and, more recently, on geographic information systems such as the APLIS method (Andreo et al. 2008; Marín 2009), among others.

The analysis of the piezometric surface, hydraulic conduc- tivity data and the geometric features of studied aquifers may- be of great interest in the assessment of groundwater flow and yield at aquifer scale (Andreo et al., Centre of Hydrogeology of the University of Malaga, unpublished data, 2010; Zuffianò et al. 2016). The flow conceptualization performed from hydrogeological data needs to be validated using numerical models for the simulation of relevant processes (Romanazzi and Polemio 2013). The visible groundwater discharge com- ponent is a priori easy to determine because it can be assessed through direct flow measurement, using traditional techniques such as the velocity-area and the salt dilution methods or novel measurement techniques (e.g. ultrasonic flow meter). However, hidden outflows may exist, both towards neighbor aquifers (or sectors within the same system) or, in the case of coastal aquifers, into the sea via coastal or SGD (Espejo et al. 1988; Garcia-Solsona et al. 2010a; Mejías et al. 2012). For the latter, indirect quantification is usually performed by rearranging the output component and solving it in the water budget equation.

More recent advances in the accurate identification of SGD can be conducted by using specific methods such as the anal- ysis of airborne thermal infrared images or oceanographic sur- veys (Mejías et al. 2012; Tamborski et al. 2015; Swarzenski et al. 2016); however, these techniques require complicated and expensive logistics and do not provide flow estimation. The quantification of onshore groundwater fluxes to the sea can also be performed by means of chemical tracers such as salinity, and radioactive isotopes, mainly ^{223}Ra, ^{224}Ra and ^{222}Rn. Ra iso- topes have been applied as characteristic markers of SGD in numerous aquatic systems, mainly because they occur naturally (in SGD, they are found in higher concentration compared to the coastal seawater) and behave conservatively in seawater, but also because their half-lives vary in a wide range, permit- ting SGD processes to be characterized at different time-scales (e.g. Moore 2006; Charette et al. 2013; Rodellas et al. 2015a). ^{222}Rn is also employed to quantify SGD because it is chemi- cally conservative and its main source in coastal areas is usually groundwater discharge, although its evasion to the atmosphere makes it difficult to estimate accurately the water outputs (e.g. Burnett and Dulaiova 2003; Stieglitz et al. 2013). Several stud- ies have used these tracers to quantify SGD at coastal areas, but there has still been limited research on the quantification and significance of SGD in karst aquifer systems (Garcia-Solsona et al. 2010a, b; Gonneea et al. 2014; Tovar-Sanchez et al. 2014; Rodellas et al. 2015b).

In this study, a multi-method approach comprising different but complementary methodologies for assessing aquifer re- charge (Thornthwaite, Kessler and APLIS methods) has been applied to get a reliable evaluation of the groundwater re- sources of the Sierra Almijara carbonate aquifer (Southern Spain, Fig. 1). The ambiguity of water budget calculations has been reduced considering the total inland discharge (spring flow, groundwater diffuse discharge to the rivers and pumping abstraction) and groundwater volume drained direct- ly from the aquifer to the Mediterranean Sea. The latter water component has been assessed using isotopic techniques (^{223}Ra and ^{224}Ra). The integration of all these quantitative results constitute a significant advance in the knowledge on the transference of water fluxes within the aquifer, providing simultaneously more accurate quantification of groundwater recharge and aquifer discharge, but also by evaluating the significance of SGD.

Background information

Location and climate

The test site (Sierra Almijara) is situated approximately 60 km to the east of the city of Málaga (Fig. 1), in the homonymous province (S Spain). It is included in the Natural Park of Sierras de Tejeda, Almijara and Alhama (407 km^2), which is consti- tuted by inland mountainous relief ending in a coastal area. The topography is highly abrupt, with steep slopes and an altitude interval ranging from 0 m above sea level (a.s.l.) at

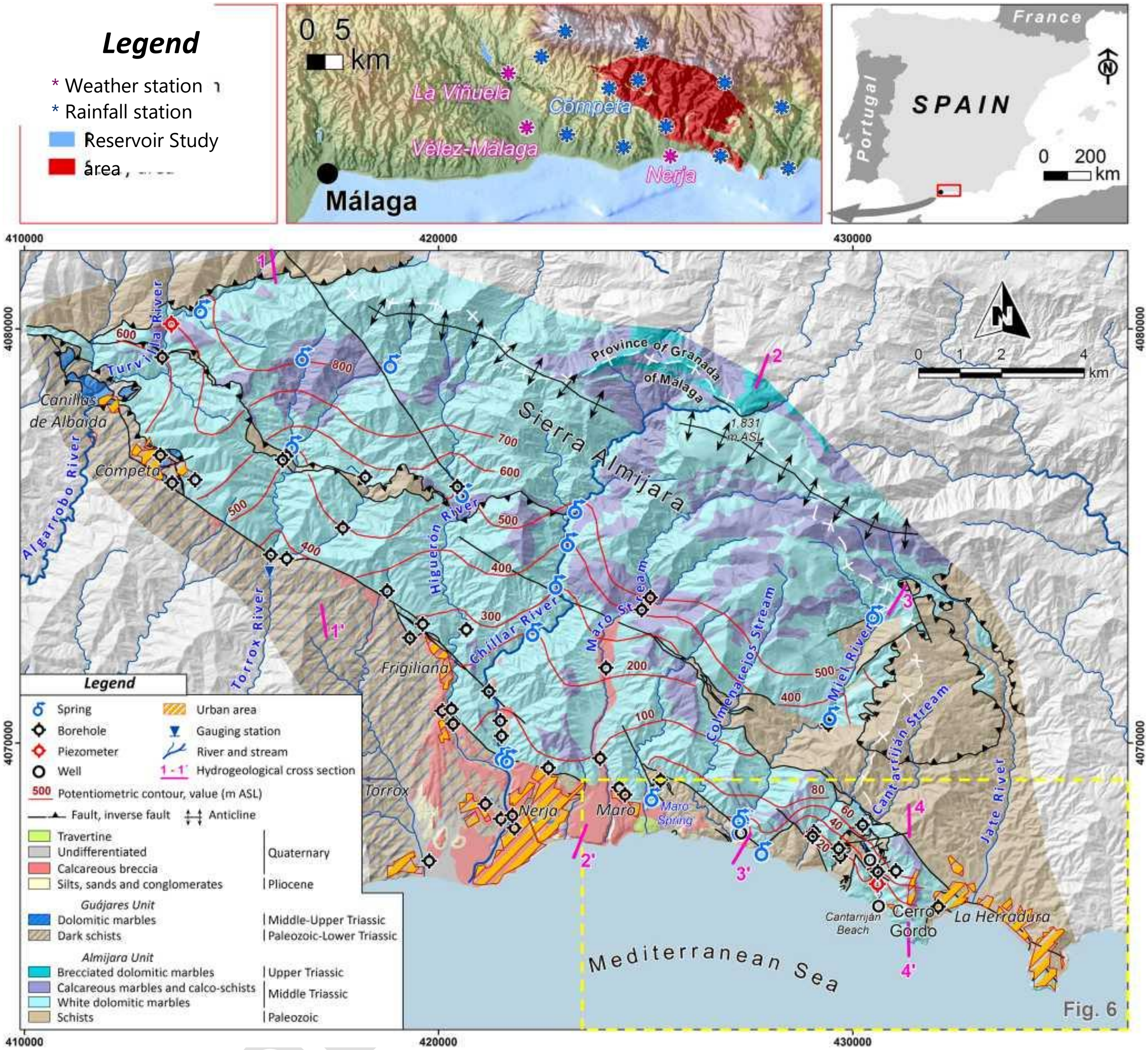


Fig. 1 Location of the study area and the main geological, hydrogeological and climatic features. The potentiometric surface of the Triassic carbonate sequence of Sierra Almijara aquifer (2006/2007 hydrological year) is also displayed

the shoreline, to 1,831 m a.s.l. in the highlands, just several kilometers from the coast (Fig. 1).

The prevailing climate is of Mediterranean type. Rainfall occurs predominantly in autumn and winter and less frequently in springtime; its spatial distribution is mainly conditioned by the altitudinal gradient. In general, precipitation progressively increases towards higher altitudes, from 400 mm at the shoreline to more than 1000 mm over the highlands. Average historic annual rainfall (1942/1943 to 2005/2006) is approximately 700 mm (Andreo et al., Centre of Hydrogeology of the University of Malaga, unpublished data, 2010). Figure 2a shows the rainfall distribution at the Nerja weather station. The individual climate periods are classified according to the type of hydrological year: wet (21 years), intermediate (14) and dry (25). The transition between wet and dry pluriannual periods is also displayed (Fig. 2b). Sierra Almijara is characterized by mild temperatures during winter (12–15 °C) and a longer and warm summer period (26–30 °C). Mean annual temperature is 18 °C (Pérez and Andreo 2007).

Geologic characteristics

Geologically, Sierra Almijara belongs to the Alpujarride Complex of the Internal Zone of the Betic Cordillera (Elorza and García-Dueñas 1980; Avidad and García-Dueñas 1981). The lithological sequence of Almijara geologic unit is

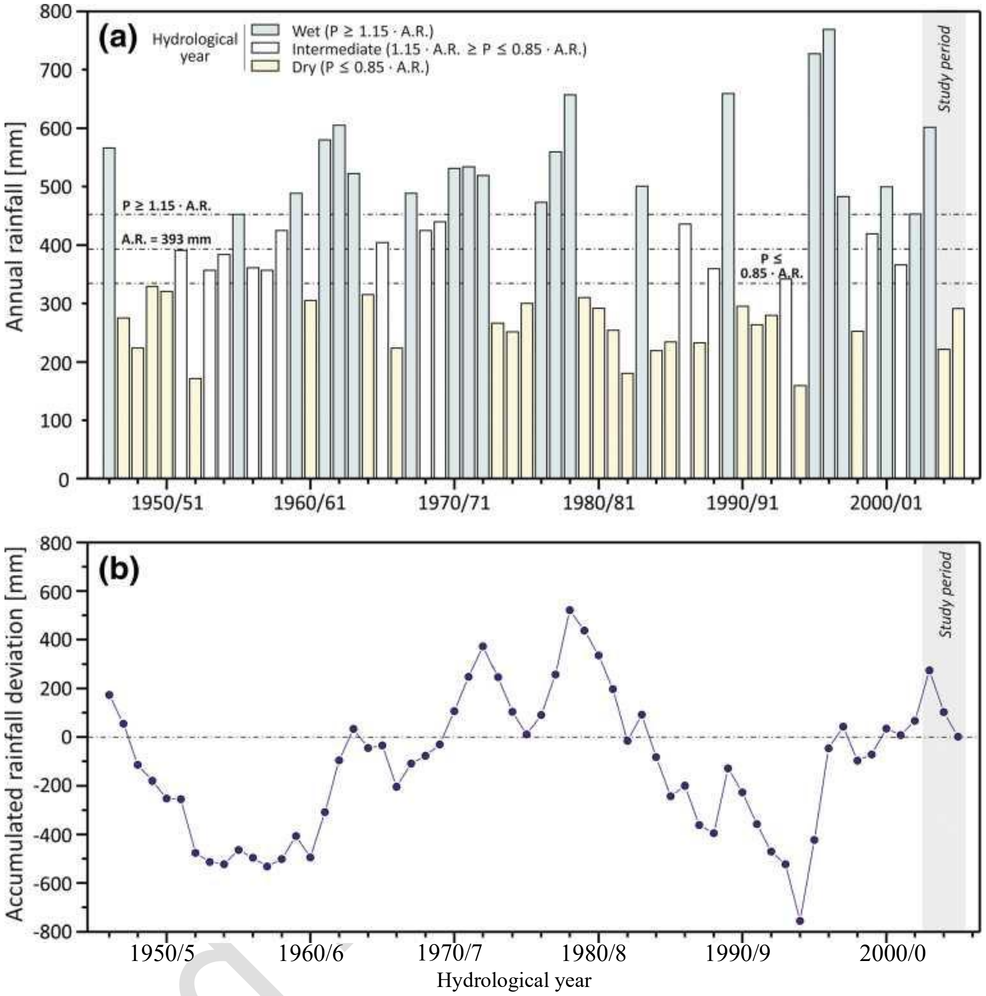


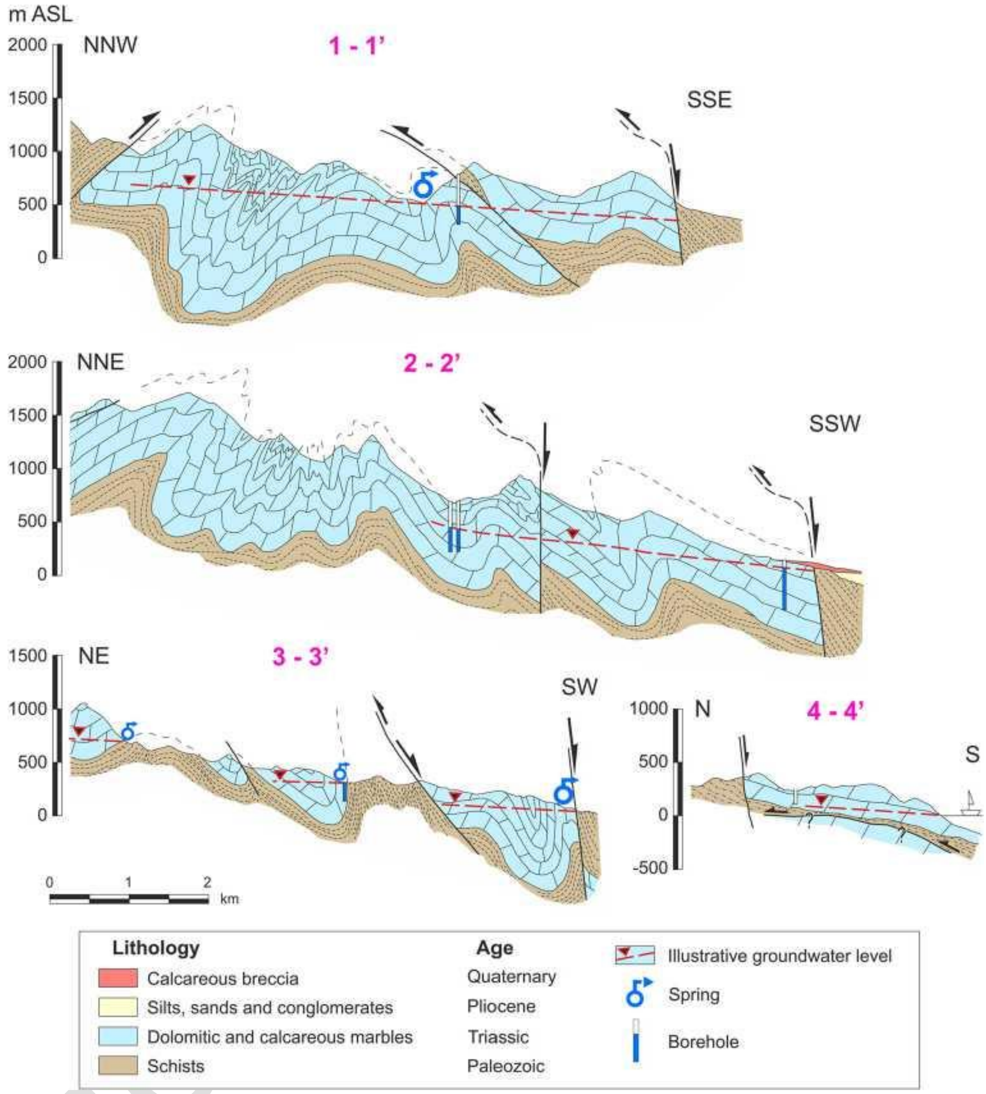
Fig. 2 Annual a rainfall distribution and b its accumulated deviation at the Nerja weather station (recording period 1942/1943 to 2005/2006). References to wet, intermediate and dry climatic periods are indicated

composed of metamorphic rocks (Fig. 1), including Paleozoic schists at the bottom of the stratigraphic series and Triassic marbles at the top. The latter rocks are also classified into three geologic formations (Fig. 1; Sanz de Galdeano and López-Garrido 2003): fissured white dolomitic marbles (lower position, Middle Triassic age), with 500 m of maximum thickness, which extensively crops out in the southern half of the study area; calcareous marbles (intermediate position, Middle Triassic age), 30–100 m thick, with interbedded (dark) calcoschists; and white-gray dolomitic marbles (Upper Triassic) with a thickness of 400–500 m, which are greatly brecciated. Paleozoic dark schists, which are associated with an upper tectonic (Guájares) geological unit, widely outcrop to the south of Sierra Almijara (Fig. 1).

Pliocene conglomerates and sands of marine (near current coast) and continental origin (in the surroundings of the highlands) also appear discordant over the main group of metamorphic rocks (Frigiliana-Nerja area; Fig. 1). Stratigraphically above the Pliocene materials, Quaternary deposits (Pleistocene breccias and upper Pleistocene travertines) are found in the vicinity of the town of Maro (Fig. 1), associated with the erosion processes of surrounding reliefs; there is also evidence of the chemical precipitation of carbonate spring waters.

The general geological structure consists of a pluri-kilometer-size anticline (Fig. 3) affecting Paleozoic and Triassic rocks of the Almijara geological unit. The anticline is bordered to the SW by the Paleozoic dark schists of the Guájares unit, through a normal regional fault (Andreo et al., Centre of Hydrogeology of the University of Malaga, unpublished data, 2010). The same geological structure is also limited by reverse faults and its hinge planes roughly coincide with the more important topographic alignments (W–E to WNW–ESE). To the west (Cómpeta area; Figs. 1 and 3), the general structure is also overthrusted over itself, resulting in associated complex geometries which are constituted by NE– SW oriented syncline (double vergent) forms with reversed flanks. In addition, the main geological units (Almijara and Guájares) are tectonically affected by a set of regional NW– SE faults (Fig. 1), which very often produce tectonic horizontal displacements of some kilometers (Sanz de Galdeano and López-Garrido 2003).

Fig. 3 Geological cross-sections showing the structural patterns of the Sierra Almijara aquifer. The directions of the geological profiles are indicated in Fig. 1. To simplify, three types of marbles have been globally considered as carbonate aquifer



Hydrogeological functioning

The Triassic marbles that are found at the southern edge of Sierra Almijara (Fig. 1) constitute an aquifer with a relatively simple geometry and form part of the southern limb of the general anticline fold (Fig. 3). The hydrogeological system (Fig. 1) is bordered to the north by the WNW–ESE core of the anticline, and to the NW, SE and south by a set of NW–SE reverse and normal faults which put in contact Paleozoic schists and Triassic marbles of the Almijara geological unit. To the south, particularly in the Cerro Gordo area (Fig. 1), Triassic marbles are hydraulically connected to the Mediterranean Sea through a narrow coastal fringe (~2 km).

Recharge in the Almijara aquifer is mainly produced by rainfall infiltration through permeable and interconnected karst features (mainly fractures, fissures, joints, etc.) developed on the surface over the Triassic marbles, which are also characterized by a low degree of inner karstification (speleological network is just locally developed). Snowmelt seepage in the highlands can also occur, but this is irrelevant for the average aquifer recharge computation. In general, groundwater movement is predominantly towards the south. The permanent rivers (Turvilla, Torrox, Higuerón, Chíllar and Miel; Fig. 1) that cross the Triassic materials constitute the main drainage axis, intersecting groundwater levels of the aquifer sectors to the south. Additionally, diffuse discharge occurs through springs that emerge into the riverbed, contributing to the surface flow of the rivers, but also through localized groundwater outputs. One of the most important is Maro Spring (Fig. 1). Fresh SGD to the sea along the Cerro Gordo aquifer sector (Fig. 1) completes the natural drainage of the Sierra Almijara system. In the current scientific literature, the term “submarine groundwater discharge (SGD)” includes both (fresh) groundwater discharge from regional aquifers and seawater recirculation through sediments, but this research explicitly focuses on the freshwater component of

SGD because it is the only component that represents the net groundwater discharge component from Sierra Almijara to the sea. Groundwater abstraction through pumping wells is used for water supply to the urban settlements (Fig. 1) Cómpeta, Frigiliana, Torrox and La Herradura, but also for irrigation in the agricultural sector.

Methodology

Recharge methods

Three empirical approaches have been considered to estimate groundwater recharge in Sierra Almijara aquifer. The soil- water balance method (Thornthwaite 1948) has been applied for the effective rainfall calculation—i.e. as percentage of accu- mulated rainfall; (Eqs. 1–3) from monthly precipitation and air temperature data recorded in the three more representative weather stations (with complete historical records) included in the pilot site and its surrounding areas (Fig. 1): Vélez Málaga, La Viñuela and Nerja. Selected soil storage capacity is 50 mm, according to the scarce representation of soil cover and its max- imum thickness (0–30 cm). The length of the climatic time series is 63 years (1942/1943 to 2005/2006) for the two first stations, and 59 years (1946/1947 to 2005/2006) for the third one.

$$R = \mathrm{RE} + \mathrm{NR} + \mathrm{AR}\ (1)$$

where R is the accumulated rainfall, RE is the actual evaporation, NR is the net (effective) rainfall and ΔR is referred to as the water budget in the soil layer potentially available for the roots of the plants. Generated runoff is assumed to be negligible due to the high permeability of the carbonate outcrops, which is in agreement with the direct observations done after rainy periods in the study area. All water volumes are expressed in mm year^{-1}.

$$\mathrm{RE} = \mathrm{PE} = K \cdot \mathrm{e} \qquad (2)$$

PE matches the potential evaporation in mm year^{-1} (equiv- alent to the upper limit of RE), K is a correction factor and e is the formula proposed by Thornthwaite (1948) for the potential evaporation calculation.

$$\mathrm{e} = \ 16\ 1{\scriptstyle |}0t \qquad (3)$$

where t is the mean monthly temperature (°C), I represents the annual heat index, and the exponent a is an empirical third- order formula containing the I parameter (Thornthwaite 1948).

Kessler (1967) developed a method for rainfall infiltration assessment specifically in karst aquifers. This method only considers rainfall data and constitutes the second empirical approach used here. Recharge rate is empirically estimated (Eqs. 4–7) taking into account rainfall measured during the first 4 months (January to April) and the last 4 months of a calendar year (September to December), assuming that pre- cipitation is concentrated in these periods. The Kessler meth- od has also been applied to the three aforementioned weather stations (Vélez-Málaga, La Viñuela and Nerja).

$$R_d = \frac{R100}{R} \qquad (4)$$

where R_d is the determinative rainfall rate (mm year^{-1}), R′ represents the rainfall measured during the first 4 months (January to April) of a calendar year (mm) and R refers to the total accumulated precipitation in the year (mm year^{-1}).

$$X = R \sim R''_m \qquad (5)$$

$$R''_m \quad \frac{\Sigma R}{n} \qquad (6)$$

$$R_c = R_d + K \qquad (7)$$

where X corresponds to the corrective precipitation rate (mm year^{-1}), R″ is the accumulated precipitation during the last 4 months (September to December) of the previous year (mm), R ″$_m$ represents the perennial average precipitation (mm) recorded in these months and n is the number of years defining the study period. Finally, R_c is referred to as the corrected rainfall (mm year^{-1}) and K is the correcting constant (summarized in the empirical table found in Kessler 1967).

The third approach used in this work consists of the appli- cation of the APLIS method (Andreo et al. 2008) but using its modified version (Marín 2009). APLIS enables one to compute recharge rate in carbonate aquifers and its spatial distri- bution in a simple and quantitative way by using geographic information (GIS) tools, from the combination of different variables (geological, geographical, climatological, etc.) read- ily available in databases of public administrations. The pa- rameters used by the modified APLIS method are: altitude (A), slope (P), lithology (L), concentrated infiltration exokarst fea- tures (I), soil type (S) and hydrogeological characteristics (F_h). The qualitative variables L, I, S and F_h are transformed and scored using classes (scoring tables), according to the method variation by Marín (2009). All variables are scored from 1 to 10, following an arithmetic progression. A value of 1 indicates minimum incidence of a variable in the aquifer recharge com- putation, while a value of 10 implicates a maximum influence. The algorithm used for aquifer recharge assessment (R, as percentage of accumulated rainfall) is defined in Eq. (8).

$$R = \frac{A + P + 3L + 2I + S}{0{:}9} \cdot F_h \qquad (8)$$

The mean value of the recharge rate (R) in the aquifer is obtained as the mean of the individual R values that match each spatial unit in the recharge map. The mean rate of annual recharge represented was grouped into five regular intervals, each one assigned to one of the following recharge classes: very low, low, moderate, high, or very high (Andreo et al. 2008).

The mean annual recharge during the study period was calculated by multiplying the annual rainfall (spatially distributed values) by the infiltration coefficient computed from (Eq. 8) and by the surface area of carbonate exposures, using spatial analyst tools in the GIS software. Additional detailed information about the methodology of this approach is described in Hartmann et al. (2014). The APLIS method has been successfully applied to other carbonate aquifers representative of a wide range of climatic and geological contexts worldwide (Farfán et al. 2010; Zagana et al. 2011; Gerner et al. 2012; Martos-Rosillo et al. 2015).

Calculation of groundwater outputs from rivers and springs

The average fresh groundwater discharge of Almijara aquifer was quantified from the regular river/spring flow measurements (in the case of rivers, by differential flow measurements to compute the diffuse groundwater component) conducted during 2003/2004, 2004/2005 and 2005/2006 hydrological years, which represent a period of intermediate climate conditions. Estimations of groundwater abstraction volumes for drinking water supply and agriculture were taken from precedent studies (Dirección General de Obras Hidráulicas, unpublished data, 1991; Pérez and Andreo 2007; Andreo et al., Centre of Hydrogeology of the University of Malaga, unpublished data, 2010).

Submarine groundwater discharge (SGD) detection using ^{222}Rn and ^{224}Ra radioactive isotopes

Measurement and sampling campaigns

The field work consisted of four sampling campaigns (two of them during September 2006, and the other two in November 2009 and September 2010) in which salinity, temperature and ^{222}Rn were measured in situ in coastal waters, and ^{224}Ra was analytically determined in the laboratory from collected seawater and groundwater samples. Whereas the sampling campaigns in 2006 were exclusively focused on sampling for ^{224}Ra determination, the field survey in 2009 was conducted to measure spatially distributed ^{222}Rn and salinity. The field survey in 2010 was conducted to collect additional water samples for ^{224}Ra analysis, as well as end-member activities. A total of 48 offshore stations and 12 inland monitoring points (wells, piezometers and springs) were sampled for ^{224}Ra determination, also for water temperature and salinity, between Maro and La Herradura towns (Fig. 1). In addition, both physical-chemical parameters and ^{222}Rn were continuously measured from a moving boat along four transects perpendicular to the shoreline at different distances to the coast (according to the sea floor bathymetry: 5, 20, 30 and 50 m water depth). The ^{222}Rn measurements were recorded using three portable RAD7 (DURRIDGE Co.) detectors connected in parallel and coupled to the air/water equilibrator system RAD-Aqua (Dulaiova et al. 2005). For ^{224}Ra isotopic analysis, a sample volume of 50–60 L was filtered through a cartridge filled with 25 g of manganese impregnated acrylic fiber at a flow of <1 L min^{-1}, to quantitatively extract the Ra isotope (Moore 1976). The same fiber without coating was also used as a pre-filter to trap the particulate fraction of the sample.

Analysis procedure for ^{224}Ra

For the radioactive isotope determinations, each manganese-impregnated fiber corresponding to a water sample was rinsed with Ra-free deionized water, to remove salt and particles that could interfere with the activity measurements. Manganese fibers were then partially dried to reach the optimal fiber/ water weight ratio for Ra measurements (0.3–1 gwater per 1 g_{fiber}; Sun and Torgersen 1998). Later, manganese fibers were placed in a radium delayed coincidence counter (RaDeCC) and ^{224}Ra activities were determined following the methodology described by Moore and Arnold (1996) and Garcia-Solsona et al. (2010a).

Results

Recharge assessment from Thornthwaite, Kessler and modified APLIS methods

The mean recharge rate calculated using the Thornthwaite method (Table 1), for a soil storage capacity of 50 mm, differs among the three selected weather stations, Vélez-Málaga and Nerja (nearer to the coast) and La Viñuela (in a more relatively inland area). The computed recharge rates range between 17%

Table 1 Average infiltration coefficients obtained from the application of Thornthwaite and Kessler hydrometeorological methods

Weather station	Altitude (m a.s.l.)	Average rainfall (R) (mm)	Average temperature (°C)	Recharge rate (as % of R) Thornthwaite	Kessler
Nerja	23	371	19	17	58
Vélez-Málaga	38	508	20	33	59
La Viñuela	272	525	19	39	58

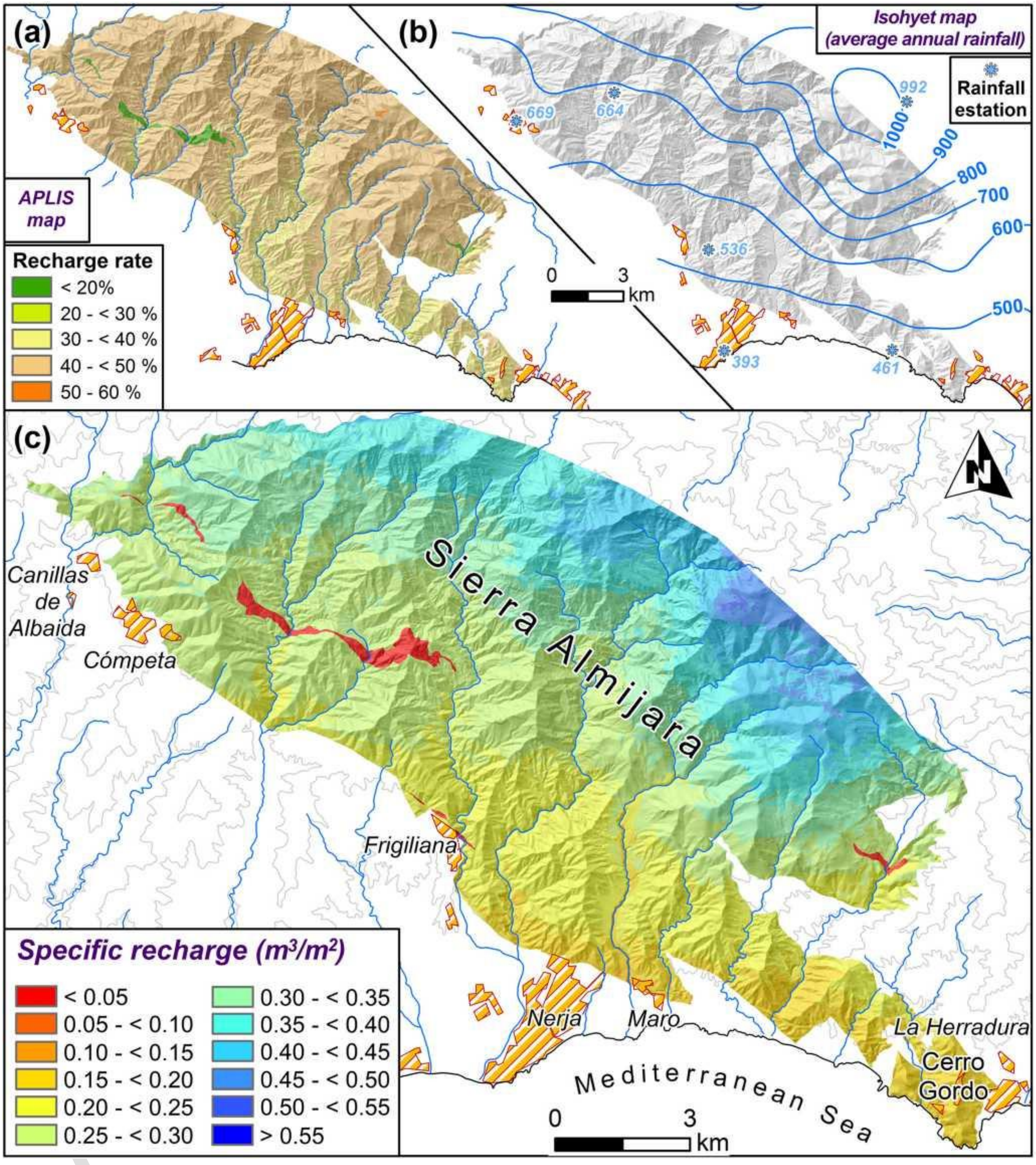


Fig. 4 a Spatial distribution of the recharge rate, b rainfall isohyets and c the specific recharge (m^3 m^{-2}) in the Sierra Almijara carbonate aquifer, obtained from the modified APLIS method

of measured rainfall (Nerja) and 39% (La Viñuela; Table 1). The mean recharge rate obtained in Vélez-Málaga station (33%; Table 1) is more similar to that of La Viñuela (this also occurs with the measured rainfall) and higher than that of Nerja station. The application of the Kessler method to the Sierra Almijara southern aquifer sector provides, from the three weather stations, infiltration coefficients of 58–59% of the precipitation (Table 1). The mean infiltration rate calculated from the spatially distributed recharge APLIS method is 42%.

Evaluation of the groundwater resources

The mean annual rainfall (700 mm) was estimated from the rainfall isohyets over the test site (Fig. 4b), which has a permeable surface area (carbonate outcrops) of 150 km^2. If both values are considered, the average precipitation vol- ume falling into the study area is approximately 106 hm^3 $year^{-1}$. By applying the computed infiltration coefficients from the selected recharge methods to the average precip- itation volume, the obtained mean groundwater resources range from 17.9 hm^3 $year^{-1}$ (Thornthwaite method, in Nerja station) to 62 hm^3 $year^{-1}$ (Kessler method, in Vélez-Málaga station; Table 2).

The mean spatially weighted groundwater resources esti- mated from the APLIS method is 44.7 hm^3 $year^{-1}$ (Table 2). Based on the rainfall isohyets map and the infiltration coeffi- cients' APLIS output map, a specific (mean annual) recharge distribution map (in m^3 per m^2; Fig. 4c) is generated. Figure 4c shows that the recharge over the carbonate expo- sures is distinctly influenced by altitude variations at the test site. In fact, at the NE border of Sierra Almijara, where the accumulated rainfall is high (~1,000 mm), the computed spe- cific recharge exceeds 0.5 m^3 m^{-2}.

Groundwater outputs

The volumes of components of groundwater discharge through permanent karst springs (study period 2003– 2006), mostly contributing to the surface flow, are summa- rized in Table 3. Maro spring comprises the most important (discrete) outlet of the Almijara aquifer system accounting for a mean discharge volume of 9.3 hm^3 $year^{-1}$ (Table 3). In the historic record of the spring discharge (Fig. 5), sea- sonal variations can be observed in response to the rainfall occurrence but no clear trend (either positive or negative) is deduced from the time-series data. Average diffuse groundwater outputs feeding permanent rivers vary from 2.6 hm^3 $year^{-1}$, in the Miel River, to 7.2 hm^3 $year^{-1}$, in the Chíllar River (Table 3). The rest of the monitored rivers show mean discharge rates of similar magnitude (3–5 hm^3 $year^{-1}$; Table 3). The time series of the Torrox River dis- charge, mainly fed by diffuse groundwater drainage, is shown in Fig. 5. As occurs with Maro spring flow, ob- served changes are due to meteoric water inputs (aquifer recharge and runoff generated upstream of the river course) and no evidence of river surface-level lowering is perceptible during the recorded period.

Table 2 Mean groundwater renewable resources (hm^3 $year^{-1}$) calculated from the application of recharge rates to the bulk mean annual rainfall over the aquifer recharge area

Weather station	Mean groundwater renewable resources (hm^3 $year^{-1}$)		
	Thornthwaite	Kessler	APLIS
Nerja	17.9	60.9	44.7
Vélez-Málaga	34.7	62	
La Viñuela	41	60.9	

The pumped groundwater volumes are certainly signif- icant in the study site (Table 3), and they are the same magnitude as some groundwater outputs feeding the main rivers. In Torrox and Cerro Gordo municipalities, water demand is 3 hm^3 $year^{-1}$, while groundwater consumption of Nerja village for drinking water purposes is 1.85 hm^3 $year^{-1}$ (Table 3). In less populated mountainous urban set- tlements, the pumped groundwater rate is 0.3 hm^3 $year^{-1}$ maximum (Table 3). Groundwater volume employed for irrigation (e.g. subtropical fruits such as avocado and mango), on average, was 4.09 hm^3 $year^{-1}$ for the 1990/1991 period (DGOH, unpublished data, 1991). Despite there be- ing no time-related evolutionary trend for well exploita- tion, groundwater levels representing the qualitative status in the northern (Turvilla piezometer) and s outhern (Cantarrijan piezometer) borders of the Almijara carbonate aquifer are displayed in Fig. 5. In both piezometers, the potentiometric levels roughly evolved in a similar way despite their distant location from each other, and they both showed a certain stability (i.e. no general decreasing ten- dency) during the recorded period.

Therefore, the sum of the mean volumes of aquifer out- puts (excluding submarine groundwater discharge), both in natural conditions and through production wells, is 44.9 hm^3 $year^{-1}$ (Table 3), which can be considered repre- sentative of intermediate climatic conditions (2003–2006 period as a whole; Fig. 2).

Salinity and ^{222}Rn and ^{224}Ra determinations

Partial dilutions of seawater (Δsalinity of 0.4–1‰) with fresh- water were mainly recorded in front of the Maro Stream and Miel River mouth as well as adjacent locations (Fig. 6), accord- ing to the salinity measurements carried out for the shallowest and nearest transect parallel to the shoreline (Fig. 6a). ^{222}Rn activities were generally low, reaching a maximum value of 34.6 Bq m^{-3} (Fig. 6b). Isotopic values significantly higher than 0 Bq m^{-3} were only recorded along the western halves of the two transects shallowest and closest to the coast (red and green lines, 5 m and 20 m, respectively; Fig. 6b). These maximum ^{222}Rn activities were recorded in the area where major salinity anomalies in seawater (up to 1‰) were found (Fig. 6b). ^{222}Rn values progressively decreased towards the east, until activities close to 0 Bq m^{-3} , as occurred in the deepest and most distant transects (blue and violet lines, 30 and 50 m, respectively; Fig. 6b). It should be noted that the high ^{222}Rn activities recorded in the transect corresponding to the isodepth of 20 m (green line in Fig. 6b) could be influenced by the high ^{222}Rn values of the

Table 3 Quantification of the annual groundwater output components (hm^3 year^{-1}) in the Almijara aquifer (study period 2003–2006). (*) Estimated value from data of DGOH (unpublished data, 1991)

Groundwater output	Monitored water point	Discharge (hm^3 year^{-1})
Diffuse discharge into the main rivers	Turvilla River	3.3
	Torrox River	4.4
	Higuerón River	5.2
	Chíllar River	7.2
	Miel River	2.6
Localized discharge through springs	Maro	9.3
	Nerja	1.9
	Árchez	0.1
	Arenas	0.1
	Canillas de Albaida	0.1
Groundwater pumping for urban use	Cómpeta	0.3
	Frigiliana	0.3
	Torrox	3.0
	Cerro Gordo	3.0
Groundwater for agriculture (*)	-	4.1
Total		44.9

shallowest transect (isodepth of 5 m; red line in Fig. 6b), which were measured immediately before, having relatively high isotope activities. This interference in the isotopic measurements derives from the equilibrium time that is needed to eliminate the remaining ^{222}Rn in the system from previous measurements.

Figure 7 displays the spatial distribution of the measured ^{224}Ra activities during the boat and field surveys of September

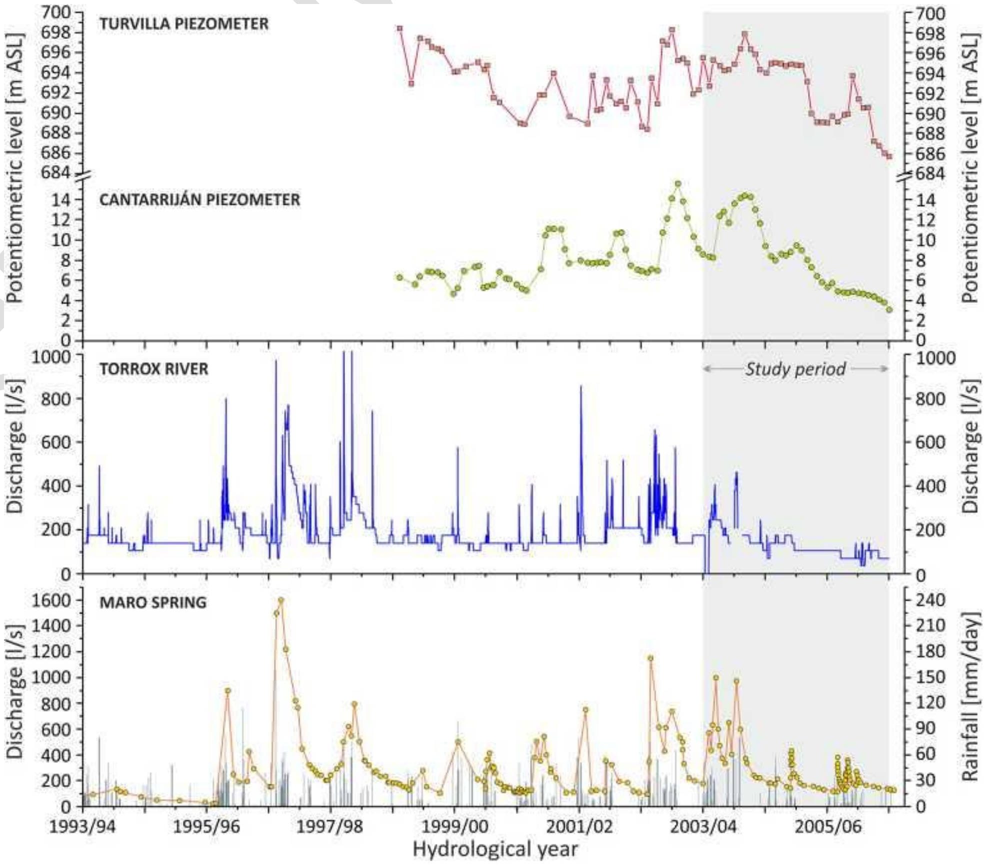
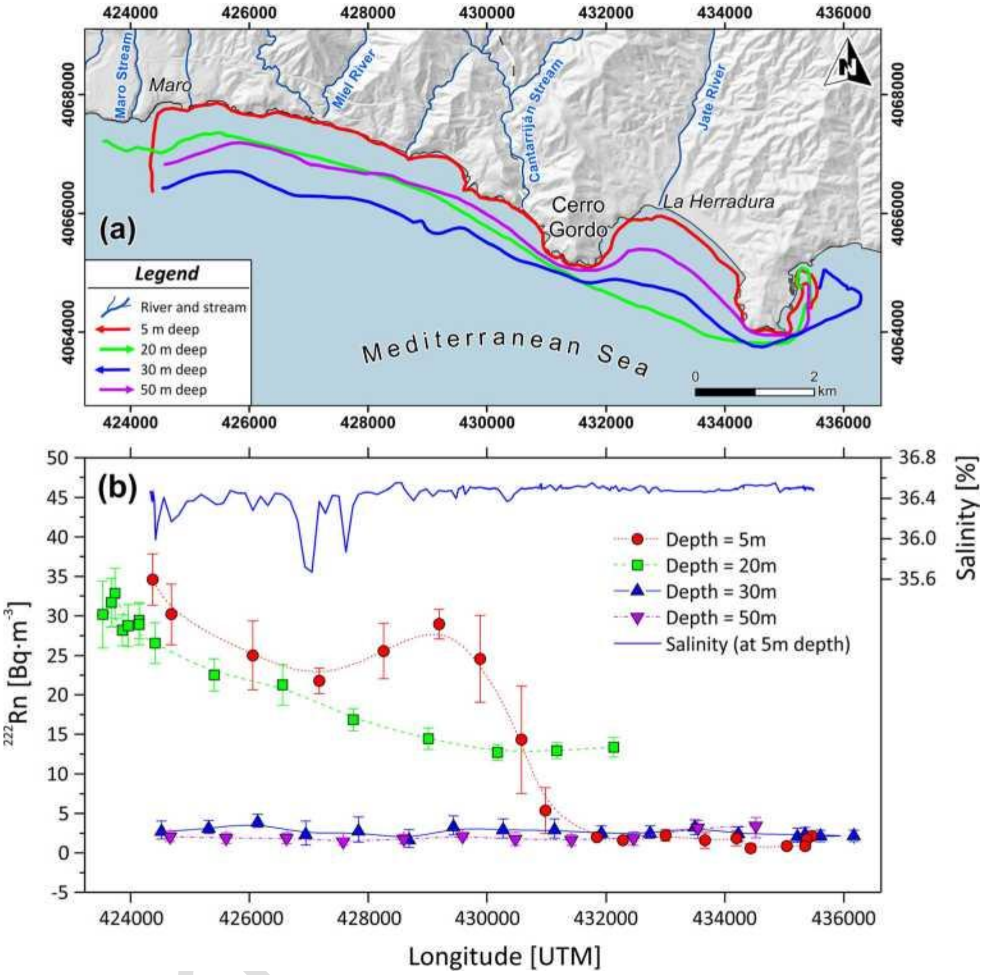


Fig. 5 Time series of Maro spring discharge (the main drainage point in the study site), of Torrox River flow and of two selected observation piezometers (located at the northern and southern sectors) in Almijara carbonate aquifer

Fig. 6 a Monitoring transects parallel to the shoreline at different depths (5, 20, 30 and 50 m) between Maro and La Herradura coastal locations, during the sampling campaign of November 2009. b Measured salinity (in the nearest transect to the shoreline, at 5 m depth) and ^{222}Rn activities along the different monitoring transects



2006 and 2010 along the Maro-La Herradura coastal line. The ^{224}Ra measurements of seawater in September 2006 showed isotope activities ranging from 2.7 ± 0.3 dpm 100 L^{-1}, in the offshore sample, to 18.7 ± 1.2 dpm 100 L^{-1}, in La Herradura beach (Fig. 7a). The ^{224}Ra activities measured in the seawater samples in September 2010 were low when compared to open coastal systems in the NW part of the Mediterranean Sea (e.g. Garcia-Solsona et al. 2010b; Rodellas et al. 2014; Trezzi et al. 2016). In addition, the maximum ^{224}Ra activities were ob- served along the shoreline where there are superficial water inputs flowing from land to sea (Fig. 7a). As an example, the highest value of 5.6 ± 0.4 dpm 100 L^{-1} was detected in the station MLG13 (Fig. 7b), which is directly related to the Miel River water contribution to the sea.

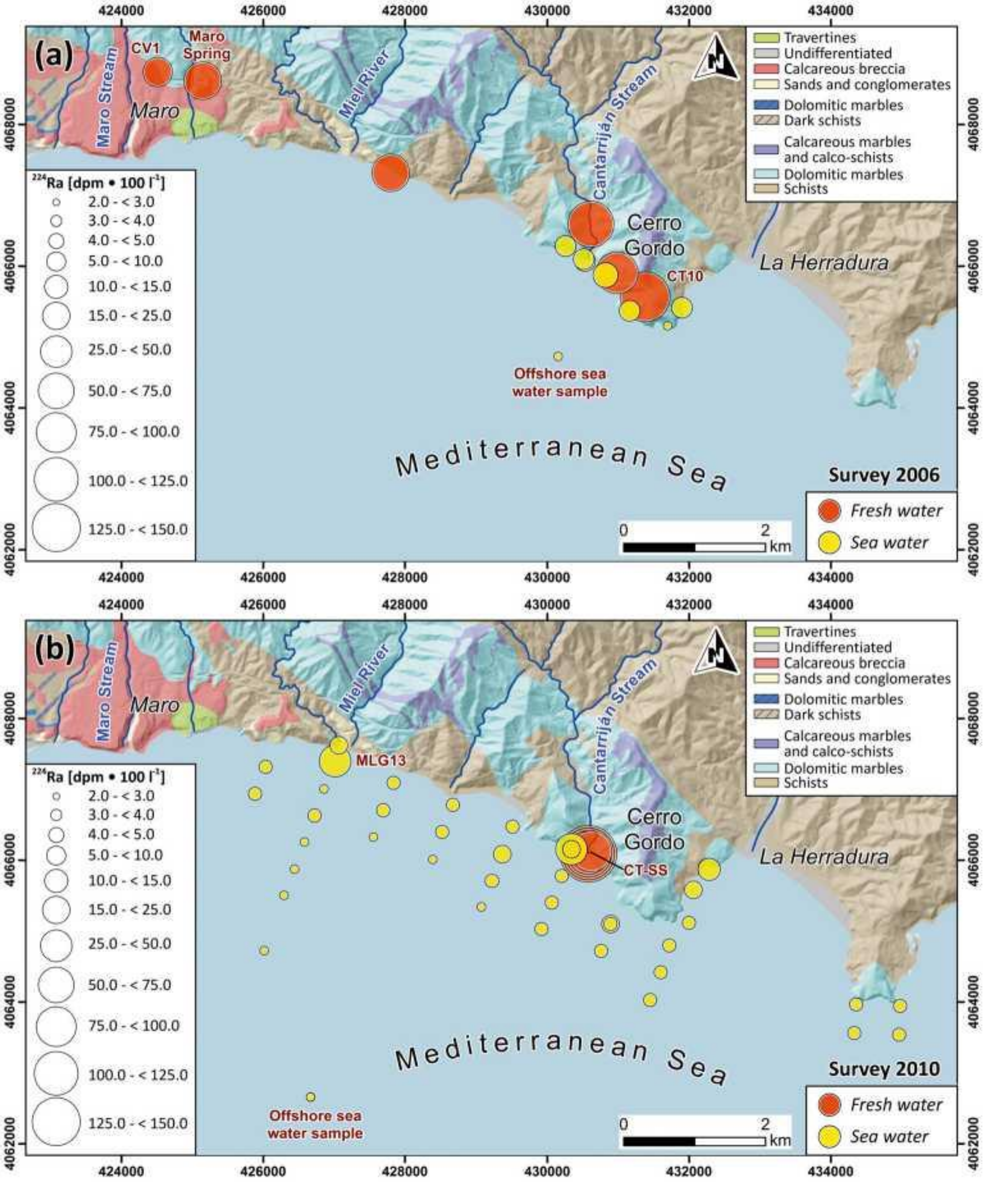
The ^{224}Ra activities of groundwater sampled in 2006 were considerably higher (of ~1 order of magnitude) than those measured in coastal seawater at the same time (Fig. 7a), with a minimum value of 18.2 ± 1.3 dpm 100 L^{-1} (CV1) and a maximum value of 126 ± 9 dpm 100 L^{-1} (CT10). The ^{224}Ra activity in the fresh groundwater sample from a well collected in 2010 (66 ±3 dpm 100 L^{-1}, CT-SS; Fig. 7b) was comparable to those isotope activities measured in groundwater in the previous surveys. Additionally, in 2010, several shallow (<1 m) piezometers were drilled in the Cantarriján sandy beach (Cantarriján stream mouth; Fig. 8), taking into consid- eration the geometric distances perpendicular to the shoreline, to measure ^{224}Ra activities of pore water within fine-medium grain size sediments (mixture of groundwater and seawater, in variable proportions). The ^{224}Ra activities determined in pore waters from these piezometers were considerably higher than those measured in fresh groundwater, with maximum activi- ties reaching 551 ± 9 dpm 100 L^{-1} (Fig. 8). The ^{224}Ra activ- ities in the pore water samples showed a strong positive cor- relation with their salinity values (Fig. 8), which reflects the salinity dependence of Ra isotopes desorption from sediments (Webster et al. 1995; Gonneea et al. 2014).

Interpretation and discussion

Comparison of the recharge methods

The estimated average net recharge of Sierra Almijara aquifer using the Thornthwaite method (17–39%, considering a soil

Fig. 7 Spatial distribution of the ^{224}Ra activities measured in the selected inland and offshore stations, during sampling campaigns of a September 2006 and b September 2010



storage capacity of50 mm; Table 1) is highly variable depend- ing on the selected rain station. The net recharge result obtain- ed from La Viñuela station (39%; Table 1) seems to be more coherent with the physiographic and hydrogeological charac- teristics of the study area. The latter station is considered the more representative among the three selected stations (Nerja, Vélez-Málaga and La Viñuela) due to its specific location (the one with the highest altitude and the most distant to the coast). Since 98% of the aquifer surface is covered by calcareous and dolomitic marbles, which are highly fissured at the ground surface and poorly karstified underground, it is expected to obtain an average recharge rate that is relatively low, similar to that estimated with data from La Viñuela weather station. However, the Thornthwaite method tends to underestimate the mean recharge under temperate climate conditions because of the overestimation of the potential evapotranspiration in karstic regions with low soil storage capacity (Andreo et al. 2008). This has been also demonstrated by Andreo et al. (2007) in the evaluation of the recharge in a Mediterranean coastal karst aquifer of eastern Spain (El Maestrazgo, Castellón province).

The application of the Kessler method provides the highest mean infiltration coefficients, around 60% for the same three climatological stations (Table 1). These results are relatively high compared to those obtained using other methods and are certainly incoherent given the lack of exokarst features at the ground surface, such as concentrated infiltration forms (swal- low holes, karrenfields, etc.) that could favor the development of preferential underground flow paths. This method was orig- inally formulated for karst (and humid) regions of Hungary; therefore, it seems to overestimate the infiltration coefficients in warmer and dryer regions as in southern Spain. This

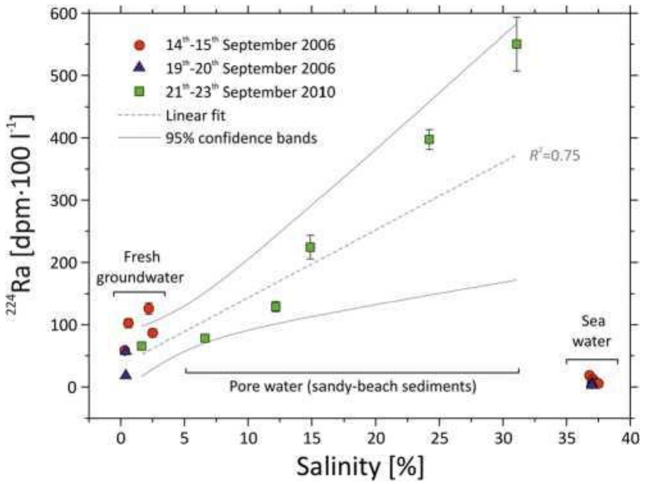


Fig. 8 ^{224}Ra activity vs salinity in spring waters, groundwater from wells and in pore waters sampled from the observation piezometers drilled in the Cantarriján beach (Figs. 1 and 6). Note that the linear fit (and the 95% confidence bands) only matches the cluster of the pore water samples. Data from open sea waters are also displayed

observation has also been reported in surrounding karst areas of Sierra Almijara (Andreo 1997; Marín 2009); hence, the Kessler method is considered to provide a rough estimation of groundwater recharge, rather than be regarded as a realistic approach whose results can be comparatively analyzed with other empirical recharge methods such as those applied here.

The average infiltration coefficient calculated from the modified APLIS method is 42%, which is close to the obtain- ed value in La Viñuela station (39%) by applying the Thornthwaite method (Table 1). Andreo et al. (2008) estimat- ed a similar coefficient (~ 43%) in the Blanca and Mijas carbonate aquifers, immediately west of the city of Malaga, hav- ing near similar physiographic and geological characteristics. The result obtained from the GIS-based method is likely the more accurate since this average percentage has been spatially weighted by considering several physical and geographical variables such as altitude, slope, aquifer lithology, karst fea- tures, soil type and hydrogeological characteristics (Andreo et al. 2007 and 2010; Marín 2009). Several authors (Andreo et al. 2007; Martos-Rosillo et al. 2013; Hartmann et al. 2014) demonstrated with success the groundwater recharge assess- ment in neighboring carbonate (karst) aquifers by applying the modified APLIS method. They also remarked on the advan- tage of this method to offer the spatial distribution of the infiltration rate, which reflects the combined influence of dominant factors such as the altitude, geomorphology (flat regions vs. steep slopes areas) and the karst development at the ground surface (density of exokarstic features), among others. By applying the average recharge rate from the modified APLIS method, the groundwater recharge is estimated to be 44.7 hm^3 year^{-1}, which represents the average renewable resources of Almijara carbonate karst aquifer for intermediate climatic conditions.

Aquifer discharge

The natural discharge of the Almijara carbonate aquifer is mainly towards its southern border (Fig. 1), through karst springs and towards the principal rivers (from west to east: Turvilla, Torrox, Higuerón, Chíllar, Maro, Colmenajeros and Miel). The rivers maintain their permanent flow as a result of the continuous diffuse discharge of groundwater. The total drainage accounted for 34.2 hm^3 year^{-1} during the studied period (2003–2006). Pumped groundwater comprises the sec- ond largest discharge volume (6.6 hm^3 year^{-1}), while the water used for irrigation (4.1 hm^3 year^{-1}, but estimated with more uncertainty; Table 3) completes the Almijara aquifer outputs; therefore, the total groundwater discharge, calculated from the previous individual output components, accounts for 44.9 hm^3 year^{-1} (Table 3).

Historically, the hidden SGD towards the sea from the Almijara aquifer has been the water (output) component most poorly constrained, due to the inherent difficulties and uncer- tainties associated with the quantification of this submarine freshwater flux. However, the results of the updated water budget show that the water inputs and outputs (without con- sidering SGD) are practically balanced, implying that the di- rect groundwater discharge to the sea should not represent a volumetrically important output during the study period. This also can be supported by the fact that the coastal fringe, by which the carbonate lithologies and the Mediterranean Sea keep in contact, is quite narrow (a little more than 2 km; Figs. 1 and 6a). Indeed, the spatial distribution of salinity and ^{222}Rn (November 2009) in seawater between the Maro and La Herradura coastal locations (Figs. 1 and 6a) showed maximum variations of ~1‰ and 34.6 Bq m^{-3} (Fig. 6), re- spectively, and are also likely influenced by (Miel) river or (Maro) karst spring inputs. These results suggest that the di- rect discharge of fresh groundwater to the sea from the Almijara aquifer is limited for average hydroclimatic condi- tions, as confirmed by the water budget calculations of the aquifer. Similar conclusions are also derived from the low ^{224}Ra activities measured in coastal waters, with maximum values associated with surface water contributions (Miel River and Maro spring; Fig. 7), confirming minimum land- based groundwater inputs to the sea in the Maro-La Herradura coastal transect. Note also that the highest ^{224}Ra activities measured in coastal waters could also be linked to the recir- culation of seawater through the sea–aquifer continuum or permeable sediments. In fact, the highest ^{224}Ra activities in end-members were measured in pore water samples with the highest salinity. The fluxes of this recirculated seawater to the sea could thus significantly enhance the observed ^{224}Ra activ- ities in the coastal fringe near to the sea. Thereby, during the study period, all evidences (the spatial distribution of salinity and ^{222}Rn data and ^{224}Ra estimates) reveal that the fresh groundwater inputs to the sea account for a minor fraction of the total aquifer recharge (44.7 hm^3 year^{-1}; from the modified APLIS method). Previously, Ollero-Robles et al. (1988) used water budget calculations to estimate the flow of fresh SGD in the same area, of ~1 hm^3 year^{-1}, which would only account for 2% of the aquifer recharge computed in this research.

Global water budget

During the few last decades, several studies have dealt with the accurate calculation of the hydrogeological balance (input and output components) in the Almijara carbonate aquifer (IGME, unpublished data, 1983; DGOH, unpublished data, 1991; Castillo-Martín et al. 2001; Pérez and Andreo 2007), but none have paid special attention to the application of a multi-method approach for recharge assessment and SGD quantification. Considering the intermediate climatic conditions, a meteoric water volume of 106 hm^3 year^{-1} falls over 150 km^2 of permeable carbonate outcrops. Evapotranspiration is indirectly quantified as 61.3 hm^3 year^{-1}, since net groundwater infiltration is 42% (44.7 hm^3 year^{-1}, by APLIS method; Table 2) of the bulk rainfall. Lateral inflows, for example from neighbor hydrogeological systems, are not likely to occur considering the geometry of Almijara aquifer and its spatial relationships with other groups of permeable rocks (Figs. 1 and 3). The natural aquifer discharge through springs and rivers, including SGD, and through groundwater abstraction, is estimated to be 44.9–45.9 hm^3 year^{-1}.

From a water budget point of view, the Sierra Almijara carbonate aquifer could be considered volumetrically in equilibrium, assuming intermediate climatic/hydrological conditions. This is because the potential groundwater excess of 1.2 hm^3 year^{-1} (difference in volume between water inputs and outputs, considering a maximum SGD of 1 hm^3 year^{-1}) could represent less than 10% of the infiltrated water volume (4.5 hm^3 year^{-1} of 44.7 hm^3 year^{-1}), which is within the uncertainty limits of all the estimated fluxes. In this way, according to Ollero-Robles et al. (1988), during dry years the SGD volume tends to be zero and even the water budget of the aquifer can be negative (the input water volumes are lower than the output ones), promoting salt-water intrusion processes.

Although the obtained recharge and discharge estimates have been computed in this research from different study periods, these ones represent and/or approximate to average conditions. The assessment of the aquifer recharge rate considers an intermediate climatic situation (occurrences of wet and dry periods are practically balanced; Fig. 2), from rainfall records of 59–63 years length. On contrast, discharge outputs refer to distinctive periods: natural aquifer discharge (2003–2006), pumped groundwater volume (2003–2006 for urban use and 1990–1991 for irrigation purposes) and SGD (estimates from September 2006, November 2009 and September 2010 field campaigns). Study period 2003–2006 comprised one wet year and two dry years (Fig. 2), and therefore, on average, matches an intermediate climatic period. The quantification of groundwater volumes abstracted for irrigation has been associated with more uncertainty, as well as a lack of trend over time, since just a discrete estimation is available. However, groundwater pumping rate (for irrigation) is assumed to have kept stable or even tended to have decreased since 1998, when the opening of the Viñuela dam permitted supply of surface water surplus for agriculture (60%) and urb an (40%) usage. Moreover, the time-series of the aquifer discharge (through Maro spring and towards Torrox River) and groundwater levels in the northern and southern sectors (Figs. 1 and 5) do not display any significant trend that could indicate water lowering in the aquifer along the historic record. Lastly, the three field campaigns for SGD quantification were performed during dry-intermediate water years and, therefore, the computed values approximate more readily to the lower limit (SGD ~0 hm^3 year^{-1}) than the higher ones.

Conclusions

A multi-method approach for groundwater resource assessment and submarine groundwater discharge (SGD) quantification in coastal carbonate aquifers has been proposed in this work, by investigating the Sierra Almijara aquifer (Southern Spain). This approach is based on the water budget of the aquifer, by providing more accurate groundwater recharge and aquifer discharge estimates, but also by evaluating the significance of SGD. The combination of hydrometeorological methods (Thornthwaite and Kessler methods) and a GIS-based approach (APLIS method) coupled with the analysis of the spatial distribution of salinity and ^{222}Rn activities, as well as the abundance of ^{224}Ra in the coastal seawater, have proved to be particularly useful for the computation of all the water budget components in the coastal carbonate aquifers. In these aquifers, Darcy’s Law is hardly applicable to obtain SGD and, as consequence, the proposed approach becomes potentially transferable to other Mediterranean (but also worldwide) carbonate karst coastal aquifers.

The obtained average infiltration rates in Sierra Almijara— for intermediate hydrological conditions—ranged between 17% (Thornthwaite) and 60% (Kessler), with 42% (modified APLIS) being the most acceptable calculated coefficient. The computed groundwater renewable resources were estimated to be 44.7 hm^3 year^{-1} on average, while the natural aquifer discharge and groundwater abstraction volumes were quantified as 44.9–45.9 hm^3 year^{-1}, also considering intermediate hydrological periods. The SGD evaluation, derived from the analysis of the spatial distribution of ^{222}Rn, salinity and ^{224}Ra during the studied period, suggests that fresh groundwater discharge to the sea in the Maro/La Herradura coastal area is not volumetrically relevant (1 hm^3 year maximum) in terms of the water budget (<<10% of the annually recharged water). From the quantification of input and output volumes, the global water budget of the Sierra Almijara aquifer can be considered in equilibrium during the investigation period (2003–2006).

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[2] Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Catalonia, Spain