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Review on groundwater recharge in carbonate aquifers from SW Mediterranean (Betic Cordillera, S Spain)

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Abstract This paper presents a review of groundwater recharge assessment in some 50 carbonate aquifers of the extreme SW Mediterranean domain (Betic Cordillera, southern Spain), an area highly vulnerable to climate change. The selected aquifers represent a broad range of meteorological and geological conditions, and consequently results can be expanded eastward to other Mediterranean aquifers. The methods most commonly applied for recharge assessment over the past 20 years are aquifer water budget and soil water balance. While these methods support the first steps in groundwater management in Spain, precision in quantification requires other methods to be incorporated. They include chloride mass balance, diverse lumped model codes and empirical methods such as APLIS. In eastern areas of the Betic Cordillera, where semiarid conditions prevail, lumped and distributed models for recharge assessment and calibration are based on the time series of water table data. The mean annual rainfall, recharge and coefficient infiltration (as percentage of rainfall) are, respectively, 648, 262 mm/year and 38 %. A high correlation was observed between annual rainfall and annual recharge in all the studied aquifers. However, the infiltration coefficient can vary substantially even with the same annual rainfall recharge. This reflects significant differences in the degree of surface karstification and the development of the vegetal cover–soil–epikarst system in the carbonate aquifers of the Betic Cordillera. The results of this work may serve to improve the assessment and management of renewable water resources in western Mediterranean carbonate aquifers. The findings are moreover useful for future comparisons involving recharge assessments under different scenarios of climate change and changes in land use.

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Introduction

In the extreme western Mediterranean, where semiarid conditions characterize some areas, groundwater is essential to supply the population, maintain associated ecosystems and support agricultural and tourism activities. The pilot sites of this research are carbonate outcrops of the Betic Cordillera (Fig. 1), extending from the province of Alicante in SE Spain to the province of Cádiz in the SW, in an area 600 km long and 130 km wide. Although the total surface outcrop of carbonate rock is not very large, aquifers consisting of limestone, dolomite and marble provide recharge rates significantly higher than detrital aquifers and low-permeability hard rocks. This fact, coupled with the good groundwater quality of carbonate aquifers and their
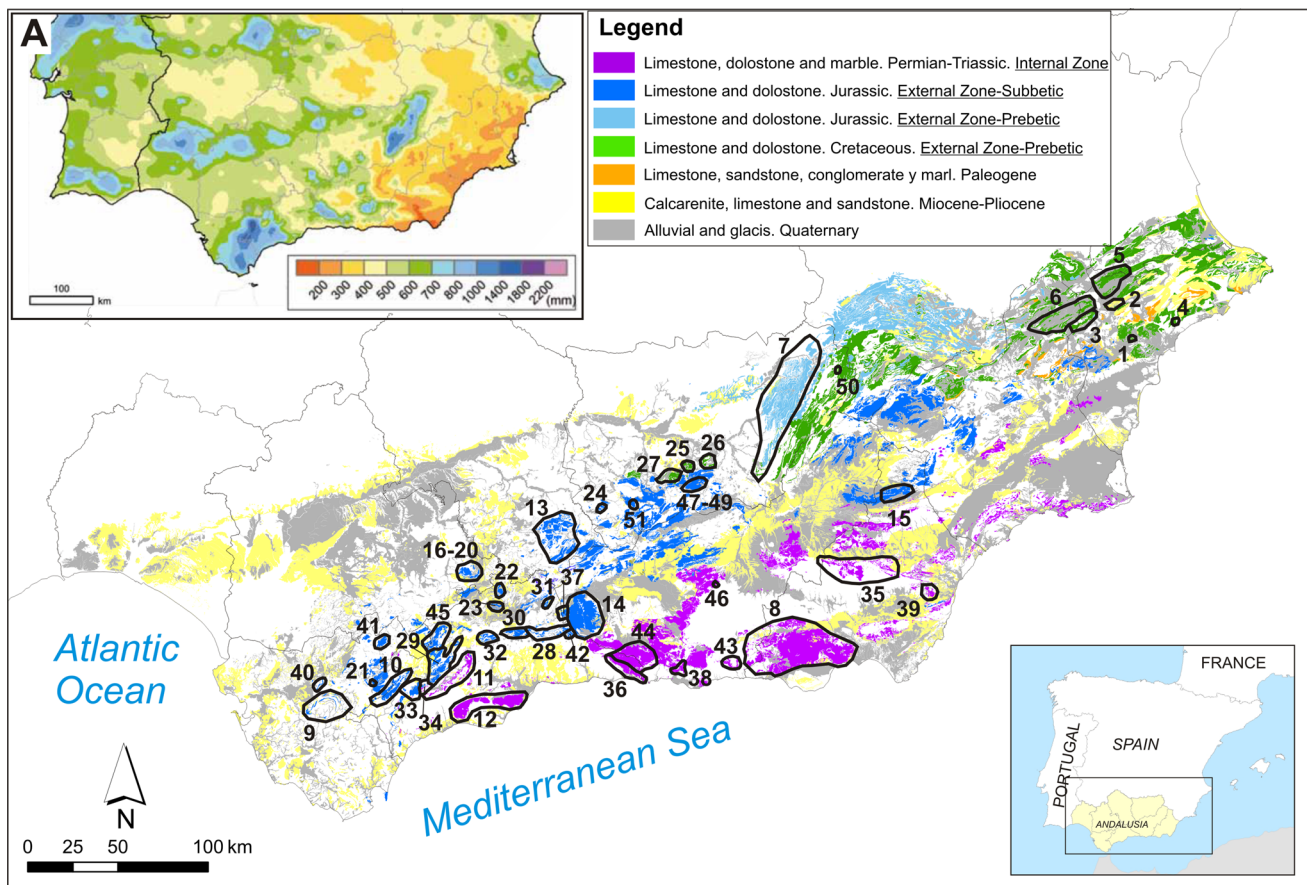
Fig. 1 Map of aquifers in Betic Cordillera. The aquifer number is listed in Appendix. *a* Mean annual rainfall in the southern Iberian Peninsula (period 1971–2000)

storage capacity, has increased the significance of these aquifers and the need to protect them. Carbonate aquifer water resources partly supply the current demand in southern Spain and are crucial to cover water demand peaks during the cyclical drought periods of the Mediterranean region. Thus, an accurate recharge assessment of these strategic reservoir systems is the key to determine the flow of sustainable yield and achieve adequate water management. In addition, the quantitative evaluation of mean annual aquifer recharge is required by the European Framework Directive (European Commission 2000).

Groundwater recharge assessment in carbonate aquifers is more difficult than in detrital aquifers (Andreo et al. 2008). The high variability of porosity and permeability of carbonate rocks influences (1) the infiltration (diffuse and/or concentrated), (2) the flow across the unsaturated zone (matrix, fractures and the karstic conduit network) and (3) the discharge (diffuse and/or concentrated) (Bakalowicz 2005; Kiraly 2003; White 1999). Moreover, to minimize the uncertainty in recharge estimation, it is necessary to generate accurate information on meteorological data, spring discharge, surface runoff, groundwater levels and

exploitation by pumping, among other aspects (Martos-Rosillo et al. 2013). Besides, several methods should be applied to minimize the uncertainty when estimating recharge (Custodio 1997; Scanlon et al. 2002, 2006).

Regarding southern Spain, recharge studies involving carbonate aquifers are relatively recent, having been carried out in the past two decades (Durán et al. 2004; Andreo et al. 2004). There have been publications in international journals (Aguilera and Murillo 2009; Alcalá et al. 2011; Andreo et al. 2008; Andreu et al. 2011; Contreras et al. 2008; Guardiola-Albert et al. 2014; Martínez-Santos and Andreu 2010; Martos-Rosillo et al. 2009, 2013; Pardo-Igúzquiza et al. 2012; Pulido-Velázquez et al. 2014). In addition, a substantial number of reports and articles have been presented and published through hydrogeological congresses and journals in Spanish (see appendix of this manuscript). The present paper is a review of the most rigorous works, written in English or Spanish, involving recharge assessment, to compare the recharge values obtained by means of several methods. The appendix offers relevant characteristics of the aquifers: annual recharge, annual rainfall, infiltration coefficient (IC), the method

applied for recharge assessment and the corresponding bibliographic references. These results are compared with other estimations for carbonate aquifers of Europe and the Mediterranean region (Alloca et al. 2014; Binet et al. 2002; Kessler 1965), particularly in southern Spain (Andreo et al. 2008).

The aim of this research is twofold: (1) to present a synthesis of the recharge rates and of methods for its assessment in carbonate aquifers from the extreme western Mediterranean and (2) to explore the relationships between the values of annual recharge, annual rainfall and IC. This analytical compilation is of special interest because groundwater recharge assessment is a key challenge in determining the sustainable use of aquifers. Furthermore, such data serve for comparative research efforts regarding the impact on groundwater reserves of climate change and changes in land use in the Mediterranean domain.

Study sites

The Betic Cordillera is an Alpine range located in southern Spain (Fig. 1), belonging to the Peri-Mediterranean Alpine orogen, formed during the Miocene. It is subdivided into the External and Internal Zones. The External Zone is made up of Mesozoic and Tertiary sedimentary rocks that were deposited on the continental margin of the Iberian plate, then folded and detached from their basement during the Lower and Middle Miocene. The Internal Zone is an allochthonous tectonic terrain from the east that disaggregated during the Lower Miocene, ejecting to the west materials (predominantly metamorphic, but also igneous rocks) that collided with the Iberian plate.

The oldest sediments appear in the so-called Internal Zone, which is located in the southern sector of the Betic Cordillera. Lithological sequences consist predominantly of Paleozoic shales and schist at the bottom, overlain by Lower Triassic phyllite and quartzite and above them thick Middle-Upper Triassic formations of dolostone and marble (both calcareous and dolomitic), sometimes with metapelitic intercalations (Sanz de Galdeano 1997). These rocks are deformed in a very complex structure involving fold nappes affected by neotectonic activity. Karstification is not highly developed, but fracturing is very intense and provokes high permeability. The aquifers tend to be large and many are close to the Mediterranean coast, meaning some of them are exploited due to the high water demand for agriculture and tourism.

The External Zone is located north of the Internal one, and is divided into the Prebetic and Subbetic. In both cases, the stratigraphic series consists of clays with evaporites of Upper Triassic (Keuper) age overlain by Jurassic dolostone and limestone resulting in high permeability due to fracturation and karstification. The Cretaceous rocks are calcareous in the Prebetic, and marly with low permeability in the Subbetic. The extension and thickness of aquifers are quite variable, given great compartmentalization caused by tectonic activity. Such division and the extensive spatial distribution make them ideal for urban water supply. At the same time, there is a great variability in the karstification at the surface and underground, being substantially more developed toward the western sector. Rainfall is generally around 2000 mm per year in the western sector, in contrast to 200 mm in the eastern one (AEMET 2001). The climate is typically temperate, with dry, hot summers. The average temperature is about 18 °C, although there are variations due to altitude and longitude. Therefore, aquifer recharge rates are conditioned by the geographic location. Other factors affecting recharge are the mean altitude of the outcropping permeable surface, the vegetal cover and the degree of surface karstification, which also decreases from W to E. The mean annual PET calculated using the Hargreaves method (1994) is around 1200 mm (Vanderlinden et al. 2008), with values for the western and eastern extremes above 1400 mm. In the central-eastern sector of the range, where the highest elevations are located, the values are around 700 mm.

Methods

This compilation of studies involving recharge assessment aims to compare recharge values obtained by different methods (see Appendix). Most studies were carried out at the aquifer scale for groundwater resource assessment and correspond to recharge directly over the outcrop area. In view of the conceptual recharge model applied in each study area, the most appropriate method was pre-selected to reduce uncertainty. The applicability of different methods is often quite limited because of scarce hydrogeological data.

The first rigorous hydrogeological research carried out in southern Spain was undertaken by FAO (1970), when the time series of meteorological and hydrogeological data were scarce and the imprecision of recharge estimation was high. The recharge was assessed in these studies using the aquifer water budget method (AWB) in some aquifers, which is adequate for a delimited aquifer when its saturated volume at the beginning and the end of the period is the same. It is necessary to know the discharge from the groundwater system and changes in the saturated volume of the aquifer. However, in many aquifers it was not possible to apply this method, and so the soil water balance method (SWB) was used. According to Scanlon et al. (2002), the major limitation of SWB proves critical when the magnitude of the recharge rate is small in relation to other variables, in particular ET (evapotranspiration) and P (rainfall).

The chloride mass balance (CMB) (Eriksson and Khunakasem 1969) has been used in previous research to estimate the total recharge originating from both diffuse and preferential flow components. This method has been recently applied in continental Spain (Alcalá and Custodio 2014) and especially in carbonate aquifers of the Betic Cordillera (Andreu et al. 2011; Alcalá et al. 2011; Martos-Rosillo et al. 2013; Guardiola-Albert et al. 2014). In some carbonate aquifers featuring watersheds with gaining stream (ITGE-COPTJA 1998), groundwater recharge has been evaluated by hydrograph separation (baseflow) and empirical approaches such as the method of Kessler (1965).

One of the most widely used empirical method is APLIS (Andreo et al. 2008; Marín 2009), designed for applications to carbonate aquifers. APLIS makes it possible to estimate the mean recharge rate (R) in carbonate aquifers, expressed as a percentage of precipitation (recharge rate), on the basis of generally available geodata of the variables altitude (A), slope (P), lithology (L), infiltration landforms (I) and soil type (S). Categories or intervals for each variable, which vary between 1 (minimal influence in recharge) and 10 (maximum influence), have been established by studying eight pilot carbonate aquifers within the Betic Cordillera and they have been displayed in a geographical information system. This permits to superimpose the layers of all variables and thus obtain the map of spatial distribution of the recharge rate and its mean value within the whole aquifer by the equation $R = (A + P + 3{\cdot}L + 2{\cdot}I + S)/0'9$. This method has been successfully tested in a lot of Spanish carbonate aquifers (Andreo et al. 2007, Martos-Rosillo et al. 2009), which are representative of peri-Mediterranean Alpine ranges according to their wide range of characteristics in terms of their climate, geology, geomorphology, topography, edaphology and hydrogeology. Moreover, APLIS has been successfully applied in karst aquifers from several worldwide countries (Farfan et al. 2010, Gerner et al. 2012).

In the eastern Betic Cordillera, semiarid conditions prevail and many carbonate aquifers are intensively exploited (Andreu et al. 2011). Further, the reduced dimensions of the permeable outcrop of the aquifers (<50 km^2), their high permeability and the long dry period occurring between groundwater recharge events can cause a fast drop in their groundwater level and the frequent disappearance of springs. Under such conditions, when pumping extractions are known and there are series of piezometric data, assessment methods based on the recharge groundwater level can be successfully applied. In this sense, ERAS (Murillo and De la Orden 1996) is a lumped model, frequently used in carbonate aquifers of southern Spain. The ERAS code is a simplified version of the MEDA code (Iglesias-López 1984) and is very similar to the cumulative rainfall departure (CRD) model

(Beekman and Xu 2003), widely used in South Africa. Application examples of ERAS in the Betic Cordillera, including comparison of the results obtained with other methods, can be found in Aguilera and Murillo (2009), Martos-Rosillo et al. (2009, 2013), Martínez-Santos and Andreu (2010) and Andreu et al. (2011).

Alternative lumped models utilized in southern Spain are the so-called VENTOS (Bellot et al. 2001) and TRIDEP (Padilla and Pulido-Bosch 2008). Recently, Pardo-Igúzquiza et al. (2012) developed a distributed model for evaluating recharge in carbonate aquifers and applied it to the pilot site of the Sierra de las Nieves aquifer (number 11 in Fig. 1). In turn, Contreras et al. (2008) used a satellite-based model to estimate potential recharge in the Sierra de Gádor aquifer (number 8 in Fig. 1).

Another interesting lumped model, providing sound results, is the VISUAL BALAN code (Samper et al. 1999). This code balances equations in the soil, the unsaturated zone and the aquifer, and requires just a few parameters. The main components of balance are the inputs by precipitation and irrigation, and the outputs by surface runoff, evapotranspiration, interception, hypodermic flux and groundwater flow. Infiltration can be computed by means of a Horton equation. The code is capable of routing water flow in the unsaturated zone toward the springs, subtracting this component from the groundwater recharge, and it allows for the calibration of parameters and key coefficients regarding piezometric level and/or flow data series. VISUAL BALAN was recently applied in the Serral-Salinas aquifers (number 3 in Fig. 1, Pulido-Velázquez et al. 2014) and in the Sierra de las Nieves aquifer (Guardiola-Albert et al. 2014).

Three-dimensional models based on numerical codes have been scarcely used in southern Spain. Martínez-Santos and Andreu (2010) compared recharge results from ERAS and MODFLOW codes in different aquifers from the southeastern Betic Cordillera. Pulido-Velázquez et al. (2014) modeled the flow and recharge of the Serral-Salinas aquifer combining VISUAL BALAN and MODFLOW codes to simulate the aquifer response to different climate change scenarios. According to Cavé et al. (2003), these methods have a great potential to forecast recharge because they establish relationships between rainfall, water level fluctuations and spring discharge.

Results

The abundant bibliographic data collected in this work (Appendix) reflect the predominantly small size of the carbonate aquifers in the Betic Cordillera, with a median value of 26 km^2 (Table 1). The Sierra de Gador aquifer (number 8 in Fig. 1) is the largest, with 823 km^2 of

Table 1 Statistical values of surface outcrop (*S*), annual rainfall (*P*), annual recharge (*R*) and infiltration coefficient measured (IC) for the 51 aquifers studied

	S (km²)	P (mm/year)	R (mm/year)	IC (%)
Mean	83	648	262	38.1
SD	156	216	146	11.8
Median	26	586	237	38.3
Percentile 10	4	414	115	25.6
Percentile 90	196	964	469	54.0
Max	823	1299	720	67.2
Min	1	242	7	2.9

Legend: *SD* standard deviation, *Max* maximum, *Min* minimum

outcrop. There are also aquifers with under 1 km² of surface outcrop (Mingo aquifer, number 17 in Fig. 1).

The mean annual rainfall on carbonate aquifers in southern Spain and its associated standard deviation amount to 648 ± 216 mm/year. The Ventos-Castellar aquifer (number 1 in Fig. 1), in the easternmost sector, receives the lowest average annual rainfall, 257 mm/year. By contrast, the aquifer of the Sierra de Libar (number 10 in Fig. 1) receives an annual rainfall of 1300 mm/year. The great variability of the annual rainfall is seen in Fig. 2a, with an evident decreasing trend eastward.

This significant spatial variability in rainfall is reflected by the variability of recharge. In this sense, recharge data presented in the Appendix correspond to precipitation directly over the aquifers outcrops. The mean annual recharge in carbonate aquifers of the Betic Cordillera may range from 7 to 720 mm/year (Table 1). The average annual recharge is 262 mm/year, with a standard deviation of 146 mm/year. The median value of recharge is 237, and percentiles 10 and 90 are, respectively, 469 and 115 mm/year. It should be noted that the high variability of the average annual recharge is influenced by the different time periods considered in each case. Recharge calculated in the reports and papers where have applied AWB method and the lumped and distributed models consider more than 4 years of measurements. In the case of the SWB method, usually more than 20 years of daily rainfall and PET data are considered. Also, application of the CMB requires, normally, 3 years more of rainwater samples, to eliminate the high variability of the chloride concentration in rainwater.

The data compiled here reveal a decreasing recharge trend toward the east, in the same direction of decreasing rainfall (Fig. 2b). Considerable recharge rates are found under favorable conditions in the western sector, between 200 and 720 mm/year. The lowest rates of recharge take place in the eastern part, where annual rainfall drops below
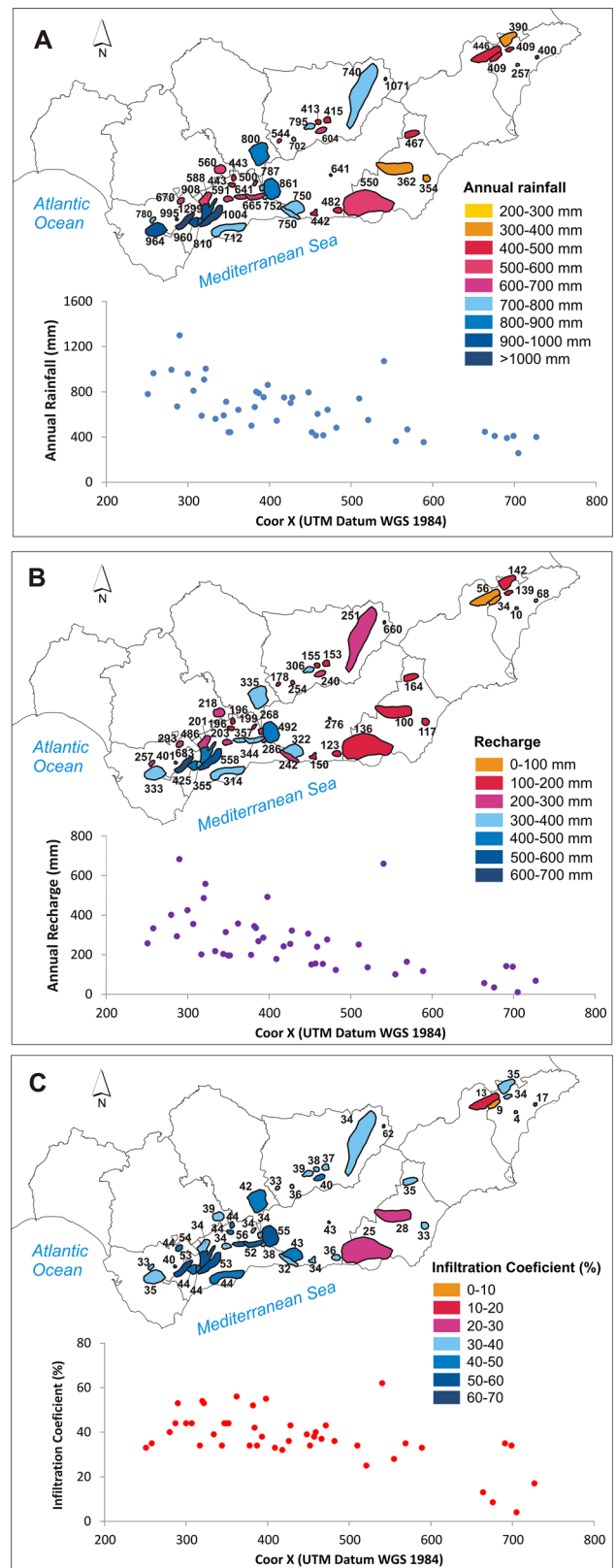

Fig. 2 Distribution of annual rainfall (**a**), annual recharge (**b**) and infiltration coefficient (**c**) in Betic Cordillera

300 mm/year. Thus, the mean annual recharge of the Ventos-Castellar (number 1 in Fig. 1) and Serral-Salinas aquifer (number 3 in Fig. 1) are, respectively, 10 and 33 mm/year. Figure 2b highlights the Sierra del Espino aquifer (number 50 in Fig. 1) recharge. This karstic aquifer is situated in the Sierra de Segura, where median annual rainfall is 1071 mm.

The average annual IC is 38 % of the rainfall, with a standard deviation close to 12 % (Table 1). Figure 2c shows that the IC is between 4 and 35 % in the eastern sector, whereas in the western part it reaches up to 55 %. The greatest IC corresponds to the Sierra de Libar aquifer (62 %); the lowest coefficient was estimated in the aquifer of Ventos-Castellar (4 %). It should be noted that Fig. 2c shows no clear decreasing trend eastward, except starting from the 500 UTM coordinate, where mean annual rainfall is low.

Figure 3a represents the annual rainfall against annual recharge, deduced using different methods. The plot shows a high and significant correlation coefficient ($R^2 = 0.83$) between annual rainfall and recharge in the carbonate aquifers of southern Spain. When the AWB, SWB and APLIS methods are applied, the correlation coefficient between rainfall and recharge is greater than 0.8. R^2 is 0.6 with the ERAS and CMB methods. Under rainfall values of 250–300 mm/year, the recharge is virtually nonexistent (Fig. 3a).

Depending on the method, as seen in Fig. 3b, there are very substantial differences (over 40 %) in the IC obtained with the same annual rainfall rate. Finally, Fig. 3c shows that most of the pilot sites have ICs ranging between 30 and 60 % of annual rainfall. The relationship between the IC calculated and the annual recharge is not linear, so that when annual recharge is higher the IC tends to stabilize, giving a coefficient near 60 %.

Discussion

In southern Spain, the assessment of recharge is essential for determining the sustainable use of groundwater from carbonate aquifers. The climatic characteristics of this region cause the recharge rates of carbonate aquifers to be low in comparison with the average annual rainfall and evapotranspiration, and thus difficult to determine precisely. Furthermore, recharge assessment in carbonate rocks is complicated by their significant heterogeneity in terms of permeability and porosity. For these reasons, choosing the most appropriate method for quantifying groundwater recharge and development depends on the conceptual model of the study area (Scanlon et al. 2002). Experience has shown that confidence in recharge assessment improves when applying a combination of different methods consistent with the conceptual model of recharge (Beekman and Xu 2003; Scanlon et al. 2002; Martos-Rosillo et al. 2013; Guardiola-Albert et al. 2014). However, in some cases the results of the methods are quite different; thus, the use of various methods shows the level of uncertainty.

None of the existing methods can be used in all situations, but at this stage the methods of AWB, SWB, CMB, ERAS, BALAN and APLIS can be applied with greater certainty in the carbonate aquifers of the SW Mediterranean region. Still, SWB and CMB entail great uncertainty, and it is recommended that they always be applied and contrasted with other methods.

It is necessary to implement spatiotemporal variable methods to better assess the recharge. Methods with great potential to forecast recharge are those that establish relationships between rainfall, pumping and water level fluctuations, such as ERAS and groundwater modeling.
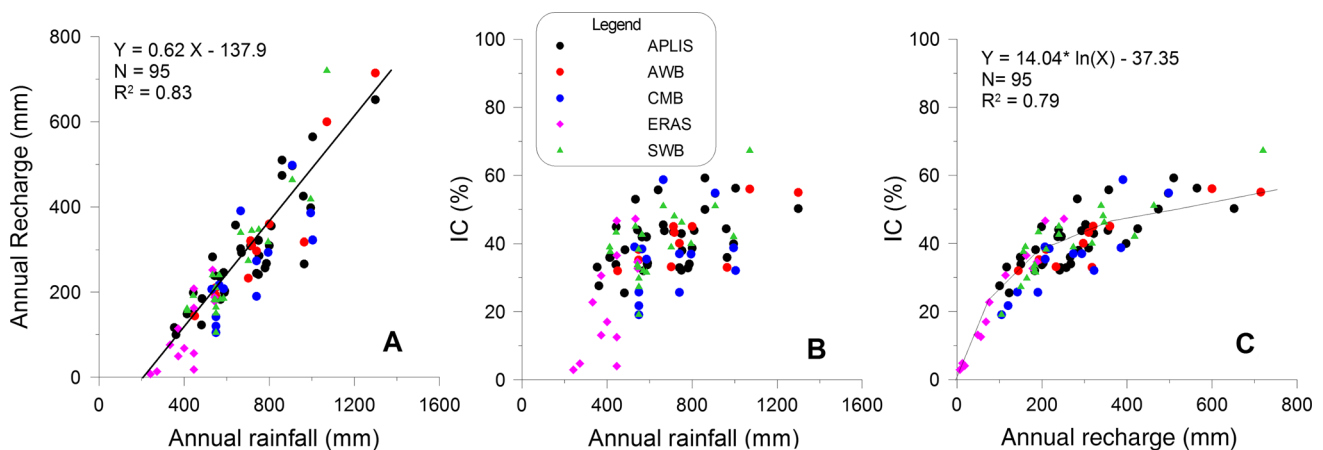

Fig. 3 **a** Annual rainfall versus annual recharge, **b** Infiltration coefficient (IC) versus annual rainfall and **c** infiltration coefficient (IC) versus annual recharge

Estimation of the IC of the 51 aquifers studied varied from 4 to 67 %, with a mean value of 38 %. Several IC estimations for carbonate aquifers have been reported for Europe. Kessler (1965) found values ranging from 7 to 70 % in Hungary. In Greece, Soulios (1984) arrived at a mean value of 50 %. In Italy, Boni et al. (1982, in Alloca et al. 2014) found values of up to 70 % for some karst aquifers in the central Apennines, and Alloca et al. (2014) reported values from 35 to 55 % in the southern Apennines. Binet et al. (2002) presented a data compilation of the ICs of various aquifers from France (Mont Ventoux, Mont Vial and Nice range, Var, Hérault) and southern Spain (Sierras Blanca and Mijas, Málaga, number 12 and Fig. 1), with values ranging between 10 and 60 %. Finally, in southern Spain, Andreo et al. (2008) reported on eight carbonate regions (aquifers number 7, 9, 10, 12, 12, 14, 15 in Fig. 1), where the IC ranged from 33 to 55 %, with a mean value of 44 %. Therefore, the IC resulting from the present review (38 %) is lower than those achieved in the rest of Europe. This would be related to the semiarid conditions of southeastern Spain. As shown in this paper, rainfall below 250–300 usually results in very low recharge, in agreement with the observation made by Scanlon et al. (2006) regarding semiarid and arid regions, and by Beekman and Xu (2003) for Southern Africa, in both cases with values under 200 mm/year.

Conclusions

In southern Spain, groundwater stored in carbonate aquifers is a strategic resource of vital importance. At present, there is increasing water demand for agricultural and drinking water (including tourism), in a scenario of drought periods and climate change. Such circumstances make groundwater recharge the principal factor in determining a sustainable management of water resources.

The bibliographic data supporting the present study correspond to 51 carbonate aquifers located in the westernmost end of the Mediterranean region and indicate mean annual recharge and associated standard deviation of 262 ± 146 mm/year. The recharge may range anywhere from 7 to 720 mm/year. The mean coefficient infiltration or recharge rate is 38 % of the rainfall, ranging between 4 and 62 %. The IC resulting from the review presented is slightly lower than that reported elsewhere in Europe, due to the semiarid conditions prevailing in the region studied.

A high correlation between annual rainfall and annual recharge was obtained for the aquifers overall. However, even with the same annual rainfall recharge, the IC can be very different. This fact points to significant differences in the degree of surface karstification and the degree of development of the vegetal cover–soil–epikarst system in the carbonate aquifer from Betic Cordillera. The influence of these factors should be investigated more in the future.

In aquifers with mean annual rainfall lower than 200–300 mm, the recharge is almost negligible. Hence, a small decrease in the mean annual rainfall volumes of the carbonate aquifers in southern Spain may translate to an important decline in the recharge of the eastern part of the Cordillera in the future.

Finally, to obtain more reliable recharge estimations, additional research should take into account long-term data series of daily meteorological data, piezometric levels, spring discharge and surface runoff. Such data should be stored and managed in centralized databases and made available to the public. Together with database management, the application of distributed models for recharge evaluation and groundwater flow models would permit for a better quantification of the impact of climate change on groundwater.

Appendix

See Table 2.

Table 2 Values of recharge estimated using a variety of methods

N	Aquifer	S (km²)	Method	P (mm/year)	R (mm/year)	IC (%)	References
1	Ventós-Castellar	7	ERAS	242	7	3.0	Andreu et al. (2001)
			ERAS	272	13	5.0	Martínez-Santos and Andreu (2010)
2	Peñarrubia	41.5	ERAS	372	114	31.0	Murillo and Roncero (2005)
			ERAS	446	163	37.0	Aguilera and Murillo (2009)

Table 2 continued

N	Aquifer	S (km²)	Method	P (mm/year)	R (mm/year)	IC (%)	References
3	Serral-Salinas	198	ERAS	372	49	13.0	Corral et al. (2004)
			ERAS	446	18	4.0	Aguilera and Murillo (2009)
4	Cabeçó d'Or	15	ERAS	400	68	17.0	Murillo and De la Orden (1996)
5	Solana	118	ERAS	333	76	23.0	Murillo et al. (2004)
			ERAS	446	208	47.0	Aguilera and Murillo (2009)
6	Jumilla-Villena	320	ERAS	446	56	13.0	Aguilera and Murillo (2009)
7	Sierra de Cazorla	823	AWB	740	297	40.0	Moral (2005)
			CMB	740	190	26.0	Benavente et al. (2004)
			APLIS	740	244	33.0	Andreo et al. (2008)
			CMB	740	274	37.0	Alcalá and Custodio (2014)
8	Sierra de Gadór	670	SWB	550	150	27.0	Pulido-Bosh et al. (2000)
			CMB	550	120	22.0	Alcalá et al. (2011)
			SWB	550	164	30.0	Contreras et al. (2008)
			SWB,CMB	550	105	19.0	Alcalá et al. (2011)
			CMB	550	142	26.0	Alcalá and Custodio (2014)
9	Sierra de las Cabras	34	AWB	964	318	33.0	Andreo et al. (2008)
			APLIS	964	347	36.0	Andreo et al. (2008)
10	Sierra de Líbar	89	AWB	1299	714	55.0	Andreo et al. (2008)
			APLIS	1299	652	50.2	Marín (2009)
11	Sierra de las Nieves	129	AWB	1004	552	55.0	Andreo et al. (2008)
			APLIS	1004	564	56.2	Marín (2009)
12	Sierras Blanca and Sierra de Mijas	173	AWB	712	320	45.0	Andreo et al. (2008)
			APLIS	712	309	43.4	Marín (2009)
13	Sierra de Cabra and Rute-Horconera	196	AWB	800	360	45.0	Andreo et al. (2008)
			APLIS	800	310	38.7	Andreo et al. (2008)
14	Sierra Gorda de Loja	334	SWB, Kessler	861	474	50.0	Andreo et al. (2008)
			APLIS	861	510	59.2	Marín (2009)
15	Sector Sierra de María Sector Sierra de María	33	AWB	450	144	32.0	González Ramón et al. (2013), IGME-IARA (1990)
		70	APLIS	484	185	38.2	Andreo et al. (2008)
16	Becerrero	26.2	SWB	586	185	31.6	Martos-Rosillo et al. (2013)
			APLIS	586	246	42.0	
			CMB	586	208	35.5	
17	Mingo	0.6	SWB	534	240	44.9	
			APLIS	534	283	53.0	
			ERAS	534	252	47.2	
18	Hacho	1.6	SWB	543	183	33.7	
			APLIS	543	239	44.0	
			ERAS	543	188	34.6	
19	Águilas	4.4	SWB	564	240	42.6	
			APLIS	564	237	42.0	
			CMB	564	217	38.5	
20	Pleites	2.9	SWB	571	183	32.0	
			APLIS	571	183	32.0	
21	Sierra de la Silla	10	CMB	995	386	38.8	
			SWB	995	418	42.0	
			APLIS	995	398	40.0	

Table 2 continued

N	Aquifer	S (km²)	Method	P (mm/year)	R (mm/year)	IC (%)	References
22	Sierra de Mollina-La Camorra	11.8	SWB	443	192	43.2	Ruiz-González (2012)
			APLIS	443	199	44.9	
23	Sierra de Humilladero	4.9	SWB	443	192	43.2	
			APLIS	443	199	44.9	
24	Ahíllo	8.1	ERAS	544	178	32.7	De Mingo (2013)
25	Torres-Jimena (Jimena)		SWB	413	161	39.0	In preparation (IGME-DPJ)
			APLIS	413	149	36.0	
26	Bedmar-Jódar	17	SWB	415	156	37.6	Mancera (2013)
			APLIS	415	150	36.0	
27	Mancha Real-Pegalajar	22.9	CMB	795	294	37.0	González-Ramón (2007)
			SWB	795	318	40.0	
28	La Alta Cadena	76	APLIS	665	303	45.5	Mudarra (2012)
			SWB	665	339	51.0	
			CMB	665	390	58.7	
29	Serranía de Ronda Oriental	104	APLIS	908	497	54.7	Barberá (2014)
			SWB	908	463	51.0	
			CMB	908	498	54.8	
30	Torcal de Antequera	28.7	APLIS	641	357	55.7	CEHIUMA (2010)
31	Sierra de Archidona	7.6	APLIS	590	199	33.8	
32	Sierra del valle de Abdalajís	40.5	APLIS	591	203	34.3	
33	Sierra de Jarastepar	45.2	APLIS	960	425	44.3	
34	Dolomías de Ronda	18.2	APLIS	810	355	43.8	
35	Sierra de los Filabres	130.4	APLIS	362	100	27.6	
36	Sierra de las Alberquillas	117.1	APLIS	750	242	32.2	
37	Sierra de Gibalto-Arroyo Marín	7.7	APLIS	787	268	34.0	
38	Sierra de Escalate	20.7	APLIS	442	150	33.9	
39	Bédar-Alcornia	20.1	APLIS	354	117	33.1	
40	Sierra Valleja	5.9	APLIS	780	257	32.9	
41	Sierra de Líjar	24.2	APLIS	670	293	43.7	
42	Sierra de Enmedio-Los Tajos	27.8	APLIS	752	286	38.0	
43	Albuñol	26.1	APLIS	482	123	25.5	
44	Sierra Almijara	70.6	APLIS	750	322	42.9	
45	Sierra de Cañete Sur	40.7	APLIS	588	201	34.1	
46	Carcabal	1.9	CMB	530	207	39.1	González-Ramón et al. (2011)
			SWB	751	346	46.1	ITGE-COPTJA (1998)
47	Mágina NE-1	6.5	AWB	548	210	38.3	Gollonet et al. (2002)
			SWB	548	181	33.0	
48	Mágina SW-1	17	AWB	717	310	43.2	
			SWB	717	344	48.0	
49	Mágina SW-2	13.4	AWB	548	193	35.3	
			SWB	548	210	38.3	
50	Sierra del Espino	2	AWB	1071	600	56.0	Moral (2005)
			SWB	1071	720	67.2	
51	Montesinos	7.3	AWB	702	233	33.2	ITGE-COPTJA (1996)
			SWB	702	274	39.0	

Legend: *N* Aquifer number, refer to Fig. 1, *S* surface outcrop, *P* mean annual precipitation, *R* annual recharge, *IC* infiltration coefficient measured. Methods: *CMB* chloride mass balance, *SWB* soil water balance, *AWB* aquifer water budget

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