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Sensitivity of a Groundwater Flow Model to Both Climatic Variations and Management Scenarios in a Semi-arid Region of SE Spain

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Abstract Since 1980, southern Spain has registered a cycle of drought with magnitudes consistent with forecasts by the European Environment Agency on climate change for a 20 % decrease in precipitation in southern Europe due to the acceleration of global warming. The impact of this climatic event has been taken into account in drawing up water management plans for the basins affected. However, it has barely been considered in terms of the evolution of groundwater reserves or in their modelling, possibly because the effects are often masked by intensive anthropic withdrawals from regional water resources. This research uses a mathematical groundwater flow model to evaluate the reserve evolution in the Mancha Oriental aquifer system (SE Spain) due to impacts from this drought cycle. Its influence has been quantified (from 1980 to 2008) in the aquifer's storage deficit 23 Mm^3/year and in the discharge volume of the Júcar River of 21 Mm^3/year. Finally, three plausible scenarios are modelled with respect to 2027, the end date of the planning horizons proposed by Directive 2000/60/EC. These scenarios examine the economic repercussions on current groundwater resource management measurements. If the drought was to persist, the costs involved in the storage deficit were calculated in the range from 21.7 to 34.9 M€.

Keywords Climate change · Groundwater pumping · Modelling · Agricultural water management

1 Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) indicates that the linear trend for planet warming over the last 50 years is almost double that for the last 100 years, and that the total temperature increase from 1850–1899 to 2001–2005 is 0.76 °C±0.19 °C. The panel also points out a decrease in precipitation in the Mediterranean area from 1901 to 2005 (IPCC 2007).

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From 1980 to the present, there has been an increase of 0.03 °C/year in the maximum and minimum temperatures compared to previous years (Bermejo and Ancell 2009), which is confirmed by studies on relations between climate change and vegetation in Mediterranean areas (García-Romero et al. 2010). In southern Italy (Campania, Abulia, and Calabria), where conditions are similar to south-eastern Spain, there has been a regional temperature increase of 0.3 °C since 1980 (Ducci and Tranfaglia 2008; Capra et al. 2013). The climate projections considered in the report Climate Change Effects in Spain (MINAM 2005), obtained using global climate models, show an increase in temperature in the Iberian Peninsula throughout the 21st century. The most unfavourable scenario predicts an average increase of 0.4 °C/decade in winter and of 0.7 °C/decade in summer.

Other studies on the evolution of hydrological events in Europe (compiled by Estrela et al. 2001) clearly detect a decrease in precipitation since 1980. In the same period, the results from the National Meteorology Institute of Spain show a precipitation drop of nearly 40 % in the southern half of the Iberian Peninsula (Pernía and Fornés 2008). In accordance with this observed trend, the report on Climate Change and the adaptation and distribution of water problems carried out by the European Environment Agency for southern Europe indicates that precipitation will decrease by approximately 20 % in this zone, which will be evidenced by fewer days of rain and by progressively drier seasons (EEA 2007).

Coinciding with these studies, a drought cycle began in SE Spain in the 80s, characterized by a widespread increase in temperatures and an average drop in precipitation throughout the period. This is commonly known to us, as the 80 Effect, a term we maintain in this work. Although emergency actions have been applied in Spain in past short drought situations, drought management plans have not been approved until mid-2007. These plans are considered as supplementary plans to the River Basin Management Plans (Estrela and Vargas 2012). As far as we know, what we have termed the 80 Effect has not taken into account in the evolution of regional groundwater reserves nor in the modelling of them for proper management, perhaps because the groundwater-80 Effect relation has always been masked by the intensive water withdrawals in the aquifers.

There are also numerous works studying the effects of climate change on groundwater in the short and long term throughout the world (in China Qian and Zhu 2001; in Central Europe Eckhardt and Ulbrich 2003; in Mediterranean area Sidiropoulos et al. 2012; in British Columbia, Canada Allen et al. 2004). There are also a number of works on hydrological modelling aimed at evaluating the impacts that groundwater extractions have on associated ecosystems (Cooper et al. 1995; Maidment and Djovic 2000; Mays and Tung 2002). These models simulate management scenarios, but always consider the same atmospheric conditions, without taking into account possible climatological changes or agricultural irrigation demands (Hanson and Dettinger 2005; Jyrkama and Sykes 2007). In addition, as pointed out by Candela et al. (2009), most research focuses on impacts on surface resources. During the last years several researches have been carried out on the impact of global warming on groundwater resources (Pernía and Fornés 2008; Hendricks Franssen 2009; Barthel et al. 2012; among others). However, as far as we are aware, there is very little information on the possible effects that the combined impacts of climate change with the management of water resources may have on groundwater-dependent ecosystems.

The main goals of this study are, first, to detect and quantify the influence of the 80 Effect on groundwater reserves and on the river discharge. Second, to analyse the possible scenarios deriving from their ongoing impact for proper groundwater resource management. The work to meet these goals is performed on one of the most extensive aquifers in Spain, the Mancha Oriental Aquifer System (MOS for short) (Fig. 1). This aquifer has been exploited since the mid-1970s, and there is a three-dimensional groundwater flow model

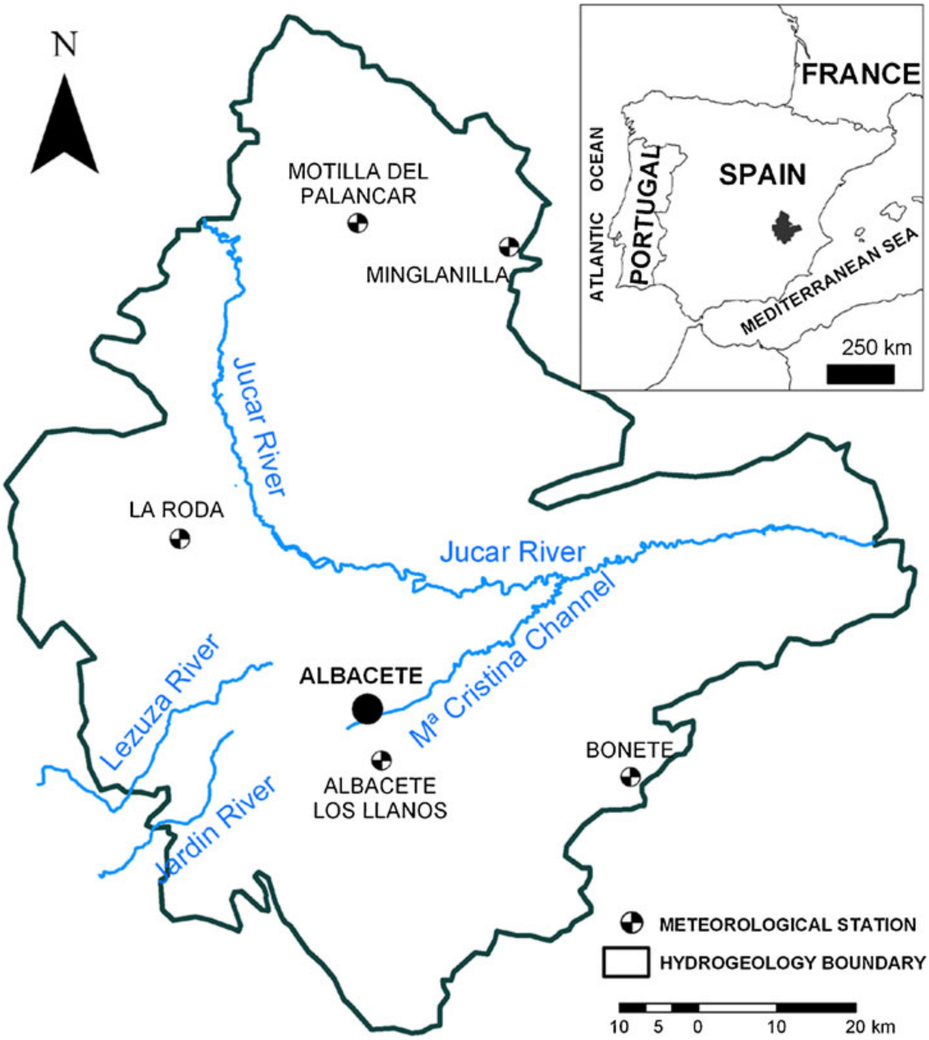

Fig. 1 Location of Mancha Oriental System (MOS)

for it that is calibrated and validated (Sanz et al. 2011). This information will assist watershed authorities in making decisions related to reaching the environmental objectives set by the European Water Framework Directive (WFD) for the year 2027.

2 Study Area

The MOS is located in SE Spain (Fig. 1). It covers 7,260 km^2 and ranges in elevation from 1,100 m in the north down to 370 m at the point where the Júcar River exits the MOS. The region is sparsely populated (approx. 250,000 inhabitants), and the largest city is Albacete (circa 170,000 inhabitants). Hydrogeologically, the MOS is a multi-layered carbonate system wherein the significant aquifer units, the middle Jurassic, upper Cretaceous, and middle Miocene, are separated by aquitards and aquifuges. The system's impermeable base comprises lower Jurassic (and occasionally Triassic) marls, clays, and gypsum. A complete description of the hydrogeological system can be found in Sanz et al. (2009), and is summarized in Fig. 2. In the steady-state flow, the main flow directions converge on the Júcar River as this is the system's main discharge (Fig. 2a). The MOS available resources in a natural regime are around 323 Million (M) m^3/year (CHJ 2004) and derive from rainwater infiltration, lateral groundwater inflow, irrigation excess, and infiltration from the Jardín and Lezuza rivers and from the María Cristina Channel (DMCC). In the transient state, the preferential direction of the groundwater flow changed in the mid-1990s from having the Júcar River as its main discharge zone (gaining river) to flowing towards the cones of depression produced by pumping, making the Júcar a losing river in some reaches (Fig. 2b).

The climate in the region is temperate Mediterranean with a continental influence, characterized by dry summers and scant precipitation. Rainfall maxima are in spring in the western sector and in the autumn in the eastern sector. Average precipitation is about 350 mm/year, ranging from 280 mm/year at the southern boundary to 550 mm/year in the northern zone, with marked interannual variations. The potential evapotranspiration (PET) of a reference crop (*Festuca arundinacea*) is about 1,200 mm/year.

Despite the climate conditions, over the last 40 years, 1,000 km^2 of dry cropland has been switched to irrigation through intensive groundwater use, which has been a key factor in the region's socio-economic development. Unfortunately, this intensive groundwater extraction (398 Mm^3/year for irrigation; 8 Mm^3/year for urban supply) has caused new problems, such as a progressive drop in groundwater levels (by about 80 m in some areas), the disconnection of surface ecosystems from the aquifers that fed them, aquifer contamination, and other issues related with the management and organization of irrigated cropland (Moratalla et al. 2008).

3 Material and Methods

3.1 Characterization of the 80 Effect

We chose meteorological data (from 1940 to 2010) from five pluviometric stations run by the State Meteorology Agency of Spain on the land surface above the MOS for which the

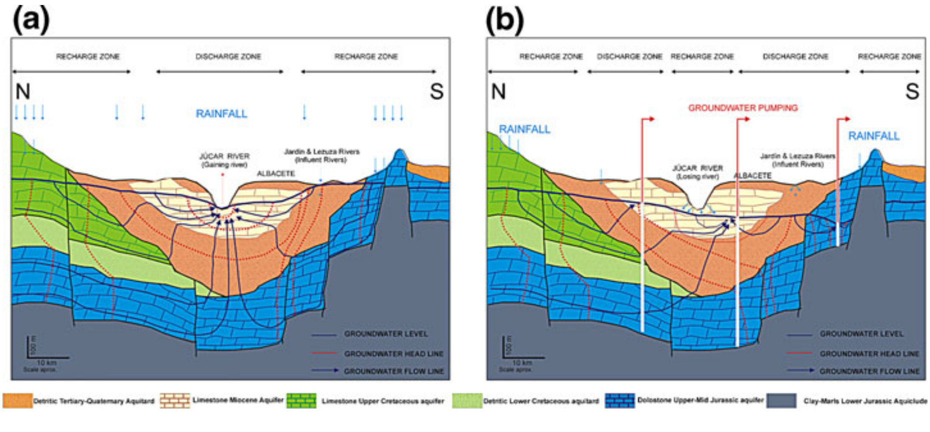

Fig. 2 Conceptual model of the Mancha Oriental System. The figure provides an overview of the hydrogeological behaviour under steady (**a**) and transient (**b**) conditions

most data was available and that together covered the entire extension of the MOS (Fig. 1). Sanz (2005) concluded that, an analysis of data from the stations initially selected shows that the MOS pluviometric variations (cumulative deviation curves) are reflected throughout the study area, probably due to the marked continental nature of the region, although there is also considerable topographic influence. Therefore, the analysis of the climatic evolution of the MOS used only data from the Albacete-Los Llanos station since it is thermo-pluviometric, representative of the zone as a whole.

The cumulative deviation curve over the average value shows two well-defined trends: a cold period from 1940 to 1980 (with an average monthly temperature of 13.3 °C), and a warmer period from 1980 to 2010 (with an increase of 1.6 °C in the average temperature, Fig. 3). The cumulative deviation curve from the average value since 1980 shows an increase of 16.6 °C, with an intensity of around 0.55 °C/year. This increase in temperature is similar to that forecast by the IPCC (2007).

There are three periods with different trends according to in the cumulative deviation curve (Fig. 4). First is a dry period ending in 1958, with a precipitation deficit of about 560 mm compared to the average. This year marks the start of a predominantly wet period that extends to 1980, with a cumulative value of 800 mm above average. From 1980 to 2007 there is a dry sequence punctuated by three wet years (1988, 1997, 1998) yet still giving a total pluviometric deficit of 600 mm compared to the average. From 2007 to the present, there is another increase in precipitation, but since the temperatures continue to increase, we are inclined to treat it as a wet period (similar to that of 1997–1998) within the general dry

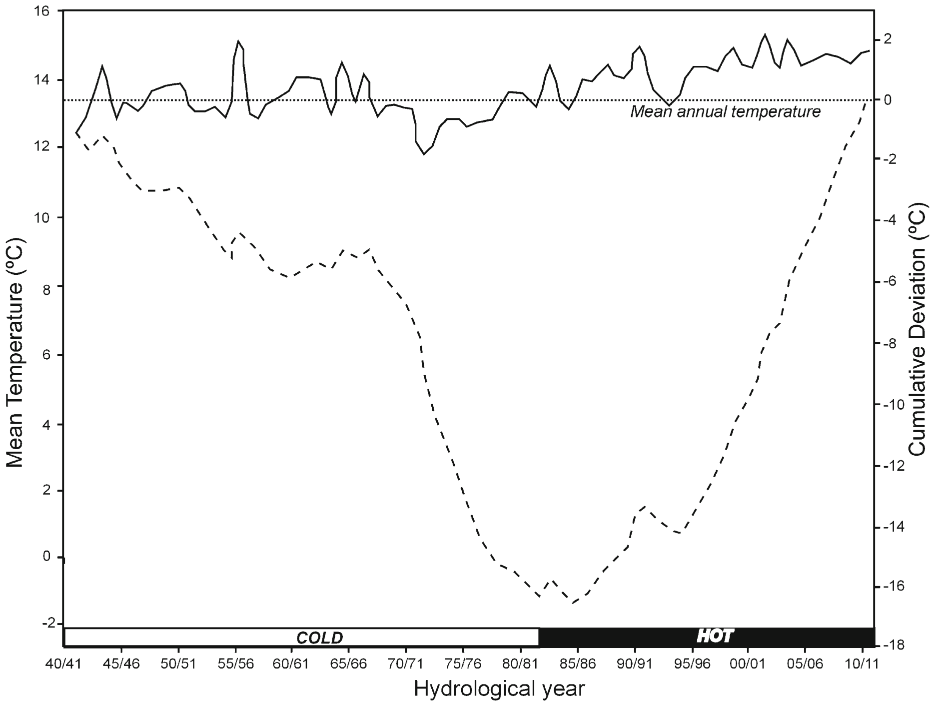

Fig. 3 Annual average temperature and cumulative deviation from the average value of the entire series. Period 1941–2010 (hydrological year). Albacete-Los Llanos weather station. Dashed line indicates the cumulative value

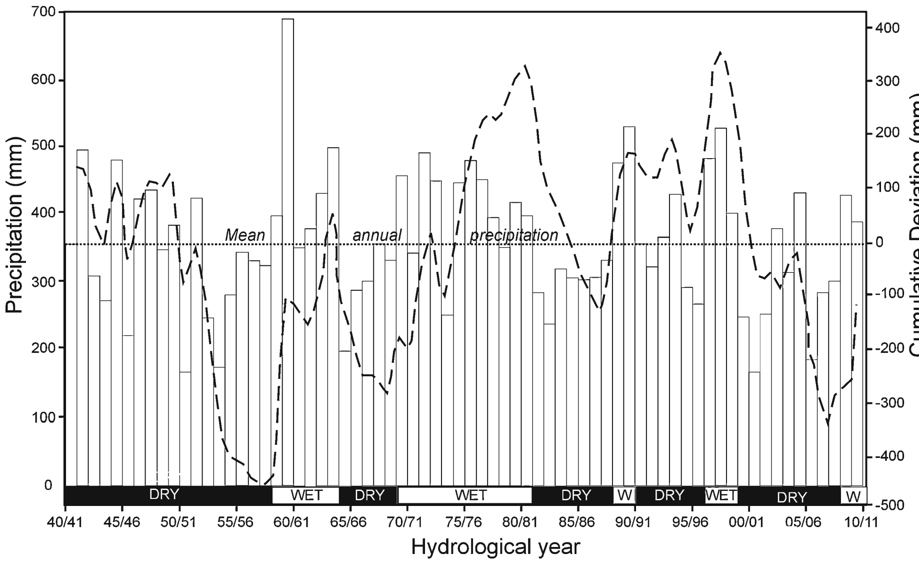

Fig. 4 Annual rainfall and cumulative deviation from the average value of the entire series. Period 1941–2010 (hydrological year). Albacete-Los Llanos weather station. Dashed line indicates the cumulative value

trend rather than as a distinct trend. What we have here termed the 80 Effect is the coincidence of a significant precipitation deficit with this warm sequence (1980–2010).

3.2 Hydrogeological Modelling

Modelling is certainly one of the best ways to handle hydrogeological data. A correctly calibrated groundwater flow model allows the spatial-temporal study of the interactions between surface ecosystems and groundwater under the effects of climate variability (Woldeamlak et al. 2007) and/or the different management measures proposed (Candela et al. 2009). The MOS groundwater flow was simulated by Modflow code (Harbaugh et al. 2000) in the Visual Modflow version (Waterloo Hydrogeologic Inc. Version 4.2) see Sanz et al. (2011) for further details). The study area was horizontally divided into 1 km-square cells aligned north–south to form a grid of 126 columns and 131 rows. The 3D geometry of the lithostratigraphic layers was incorporated, which generated a six-layer model (three aquifer units and three semi-permeable units) for a total of 99,036 cells. The hydrogeological units were hydraulically characterized, and the stress periods were taken monthly. The boundary conditions were defined by making the model boundaries coincide with the system's physical boundaries. The Júcar River was represented as a boundary condition with specific boundary potential in the study area. The recharge values due to rainwater infiltration were obtained from the application of the Patrical model (Pérez 2005). Groundwater extraction for irrigation was determined via a multi-temporal and multi-spectral analysis of Landsat TM images using the methodology proposed in Castaño et al. (2010). Groundwater withdrawals for urban and industrial use were estimated by applying a supply value to the population data for the various MOS municipalities.

In our own case, the MOS has been modelled and calibrated (Sanz et al. 2011) for a steady state and a transient state for the period 1975–2005. In this work the MOS groundwater model flow has been validated and re-calibrated with a simulation of the system in an uninfluenced steady state from 1940 to 1975 and in an influenced transient state by extending the range to 2008.

3.3 Possible Climate Change Scenarios

It is always difficult to evaluate the possible impacts of climate change on aquifers and their associated ecosystems. This is due to the uncertainty in the predictions of groundwater flow models (Konikow and Bredehoeft 1992) and, to the downscaling methods necessary to adapt global scenarios for climate-change models to regional scales (Stoll et al. 2011).

The MOS groundwater model flow was employed to simulate three scenarios that attempt to predict the MOS behaviour from 2008 to 2027 (end date of the planning horizons proposed by the Water Framework Directive of the European Parliament and Council) considering the possible impact deriving from the acceleration of global warming. To do so, we have taken into account the values obtained by simulating the groundwater flow model for the river-aquifer relations under the effects of intensive groundwater abstraction and the influence of the 80 Effect. In all three cases, the average recharge values are obtained from the monthly averages and considering three withdrawal systems (pumping of 250 Mm^3/year, 300 Mm^3/year, and 350 Mm^3/year) according to the planned extraction for the Júcar River Basin Hydrological Plan.

The first scenario (S1) assumes that the 80 Effect is merely a temporary variation with no relation to future temperature or precipitation trends. Therefore, its influence is not extrapolated and future recharge values for rainwater infiltration consider the average value for the entire 1940–2008 series (rainfall infiltration=165.4 Mm^3/year). The second scenario (S2) assumes that the 80 Effect is a change in trend arising from accelerated global warming. It considers as future values of rainwater infiltration recharge the average of the period in which the effect occurs: 1980–2008 (rainfall infiltration 20 % less=134.5 Mm^3/year). The third scenario (S3) attempts to foresee a sequence of wet years within a sequence of cold temperatures (under the assumption there is no impact from global warming). To do so, the rainwater infiltration recharge values correspond to the average for the period prior to the 80 Effect — 1958–1980 (rainfall infiltration: 236.2 Mm^3/year).

4 Results and Discussion

4.1 Evolution of Groundwater Reserves

The MOS can be viewed, in its steady state, as a huge deposit with two types of inflow: (a) Recharge from rainwater infiltration that changes over time (60–70 % of total recharge) and (b) lateral inflow and river infiltration that remain semi-constant over time (30–40 % of total recharge). Aquifer outflows occur through drainage by the Júcar River (approx. 250–320 Mm^3/year). As Sanz et al. (2009) pointed out, under these conditions storage occurs following the recharge trend and the aquifer behaves as a huge cushion of inflows produced by rainfall infiltration.

By analysing the evolution of the groundwater reserves, we hope to verify whether a mathematical model simulating groundwater flow can detect the 80 Effect in those reserves and quantify its influence on the river-aquifer relations. Clearly, it is crucial to obviate the masking effect caused by intensive anthropic groundwater abstraction, for which we used the groundwater flow model of MOS, calibrated for the steady state from 1940 to 1975. To this was added 1976–2008 data (recharge, boundary conditions, etc.) without including the installation of groundwater pumps. A total of 68 years have been simulated, for which the average recharge from rainwater infiltration does not exceed 165.4 Mm^3/year, accounting for over 60 % of the average total MOS recharge.

In the period of 1940–1956, the system discharged 1,272 Mm^3 (Fig. 5). Over the next 23 years, it recovered 1,034 Mm^3. Then, from the early 80s to 2008 (a period with intensive artificial abstractions), the aquifer lost 4,428 Mm^3. If we subtract the amount from pumping,

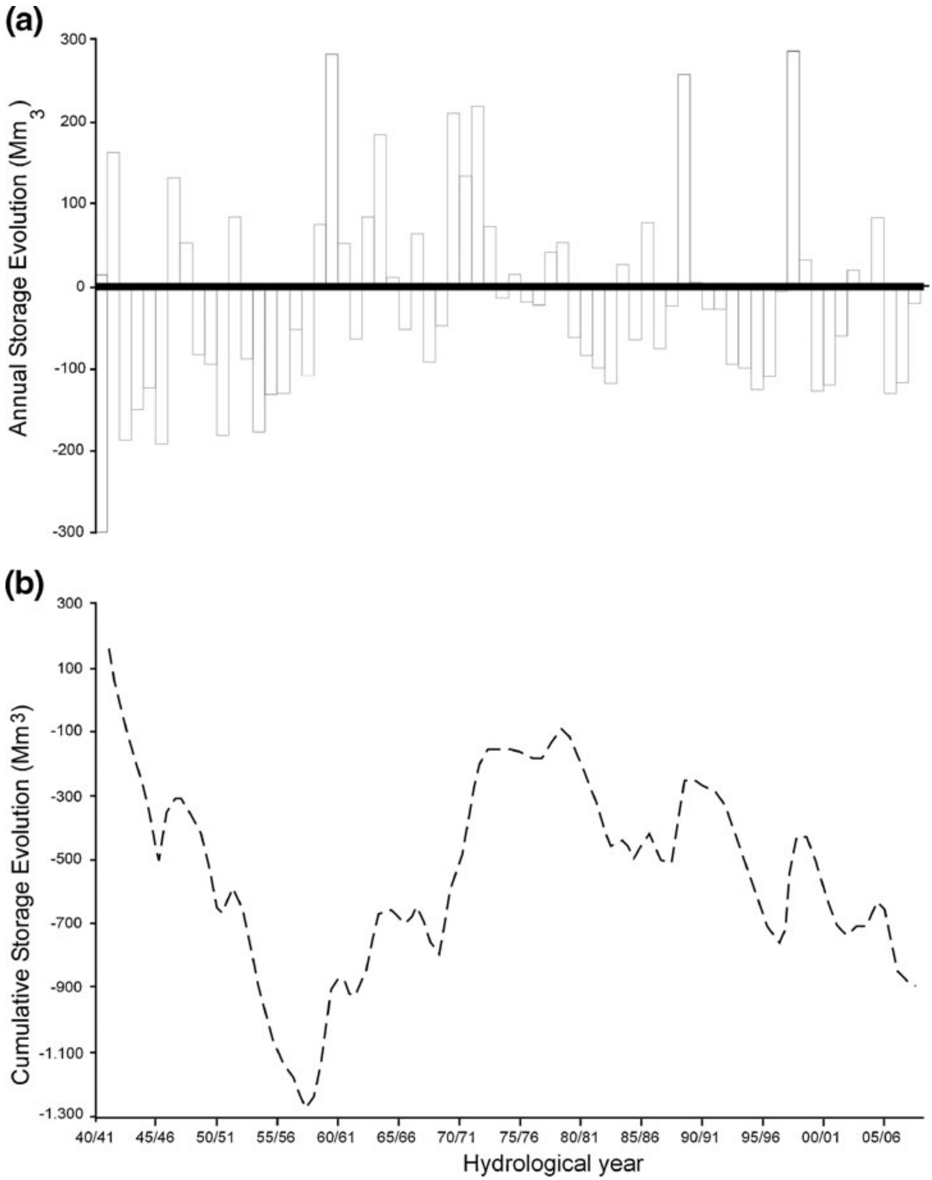

Fig. 5 Evolution of the change in storage from 1940 to 2008 without pump installation. **a** Annual Storage Evolution, **b** Cumulative Storage Evolution

the model then gives a deficit of 676 Mm^3 that is attributable to the recharge deficit — an average of 24.14 Mm^3/year.

For the entire prior period (1940–1979), which includes a wet and a dry series, the average of recharge deficit was 5.95 Mm^3/year. Thus, the deficit attributable to the 80 Effect is the difference between the two values: 18.19 Mm^3/year. This annual value represents a total of 509 Mm^3 in the period of 1980–2008. The effect of this increase in drought conditions represents 75 % of the aquifer's total natural storage deficit, but only 11.5 % of the deficit taking into account pumping.

To determine the impact of global warming on flow volumes in the Júcar River, the change in aquifer storage with and without pumping must first be analysed in order to determine the relation of the 80 Effect with the evolution of storage volumes, the repercussion of this evolution on hydraulic heads.

As concerns the global flow exchange between the Júcar River and the MOS in 1980–2008, and assuming no groundwater pumping, the Júcar River (despite the decrease in recharge from the 80 Effect) would have discharged an average of 243.43 Mm^3/year, but in fact, with the pumping, it has only discharged an average of 87.62 Mm^3/year (Fig. 6). The drought cycle has caused a deficit in aquifer discharge by the river of 620 Mm^3, which represents 11.3 % of the average volume of flow that should have been discharged by the river.

4.2 Simulated Scenarios

The simulations provided the following results for each scenario (Table 1). The first scenario (S1) assumes that future rainwater infiltration recharge will have the average

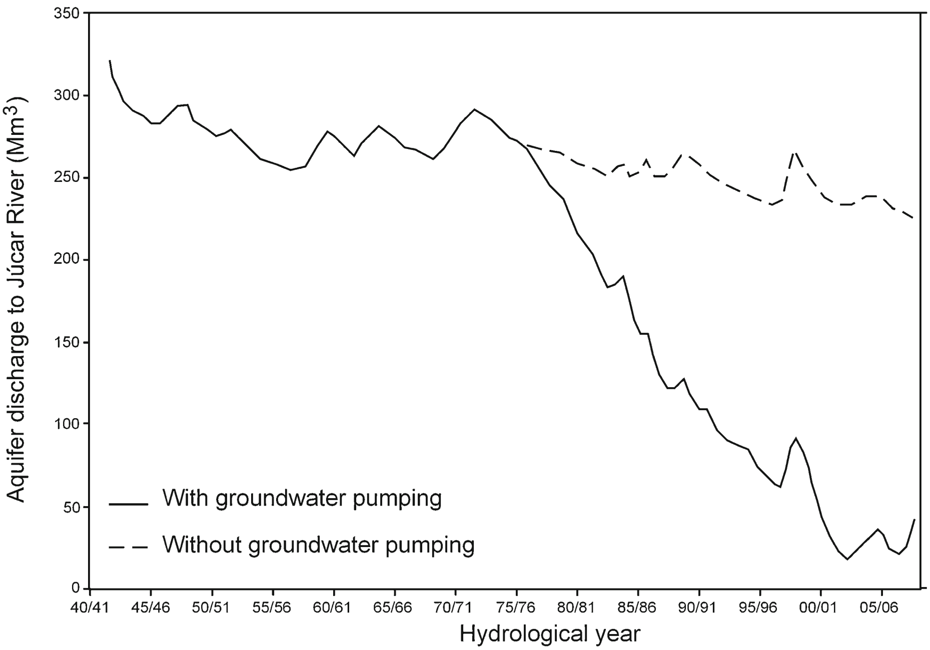

Fig. 6 Evolution of aquifer discharge by the Jucar River with and without groundwater evolution simulated by groundwater model flow. Hydrological years

Table 1 Variation in volumes of storage and river drainage in the three scenarios considered

	Period 2008–2027		Abstractions 250 Mm³/year	Abstractions 300 Mm³/year	Abstractions 350 Mm³/year
S1	Change in storage	Mm³	−669	−1,157	−1,506
		Mm³/year	−37	−64	−83
	River drainage	Mm³	1318	952	611
		Mm³/year	69	50	32
S2	Change in storage	Mm³	−1,278	−1,800	−2,065
		Mm³/year	−71	−100	−115
	River drainage	Mm³	1,225	882	560
		Mm³/year	64	46	29
S3	Change in storage	Mm³	+600	0	−200
		Mm³/year	+33	0	−11
	River drainage	Mm³	1,642	1297	976
		Mm³/year	86	68	51

value for the entire series of 1940–2008 (165.4 Mm³/year). In this case, there is a decrease in aquifer storage for all recharge and resource abstraction hypotheses. The cumulative storage decrease ranges from 669 Mm³ (37 Mm³/year) for an assumed pumping of 250 Mm³/year to 1506 Mm³ (83 Mm³/year) for an assumed pumping of 350 Mm³/year.

The second scenario (S2) assumes the 80 Effect persists and that the rainwater infiltration recharge has an average value for the period of 1980–2008 (134.5 Mm³/year). This case also shows a decrease in aquifer storage for all recharge and resource extraction hypotheses. The cumulative storage decrease ranges from 1,278 Mm³ (71 Mm³/year) for an assumed pumping of 250 Mm³/year to 2,065 Mm³ (115 Mm³/year) for an assumed pumping of 350 Mm³/year.

The third scenario (S3) considers no future effect from global warming and, instead, that we will enter a wet, cold series similar to that from 1958 to 1980. The rainwater infiltration recharge would then be the average value for the period of 1958 to 1980 (236.2 Mm³/year). This case would cause stable storage or even an increase. The cumulative storage would increase by about 600 Mm³ (33 Mm³/year) for the assumed pumping of 250 Mm³/year, it would be nearly stable for pumping of 300 Mm³/year, and would show a cumulative decrease of 200 Mm³ (11 Mm³/year) for pumping of 350 Mm³/year.

Only in the most positive case, assuming a wet series (S3), the aquifer reserves would remain stable with pumping of 300 Mm³/year. Any withdrawals under that value would allow the aquifer to recharge. In the other scenarios (S1 average precipitation, and S2 80 Effect), the aquifer reserves would fall by 669 Mm³ to as much as 2,000 Mm³ in the worst-case scenario.

The volume of flow in the Júcar River in the three scenarios is as follows: In the case of S1, the volume of flow discharged by the river for withdrawals of 250 Mm³/year and 350 Mm³/year would be on the order of 66 Mm³/year and 22 Mm³/year respectively. For S2, the river's discharge would decrease by 10 Mm³/year in all cases in comparison to the above scenario. For S3, the potential river drainage ranges from 90 Mm³/year for the pumping hypothesis of 250 Mm³/year and 45 Mm³/year for the pumping hypothesis of 350 Mm³/year.

4.3 Economic Repercussions on Water Management Measurements

In the MOS, pumping has increased nearly linearly since the early 1980s up to 2000, sharply affecting the storage and discharge of the Júcar River and turning it into a losing river in some reaches within the MOS (Sanz et al. 2011). After 2000, withdrawals stabilized or even decreased due to corrective measures implemented by the basin regulatory organism (The Jucar river basin authority, CHJ). As can be seen in Figs. 5 and 6, these corrective measures, as intended, have had more influence on recovering volumes of flow in the river than in correcting the aquifer's storage deficit. Currently, the system's storage volume is stable at the expense of an increase in river losses to the aquifer.

In our case, in the steady state, the 80 Effect has caused a deficit of 509 Mm^3 in storage and of 620 Mm^3 in river discharge for 28 years. In this situation, the planning and management policies of the basin authorities should reach the environmental aims established in the Water Framework Directive by 2027. Measures to be taken will depend on the withdrawal plans and on various scenarios for rainwater infiltration recharge. It is therefore necessary to have a clear idea of the aquifer's behaviour in these different scenarios, including those affected by climate-change impacts. The water resource management entities of any basin with significant groundwater reserves must take into account numerous scenarios in their long-term forecasts in order to undertake plans separating the effect of intensive extractions from the impact of climate change.

The long-term presence of this potential global-warming effect and its repercussions on the evolution of groundwater reserves increases the importance of prior knowledge of the effect of climate changes in the short and medium term. This knowledge is essential for the proper planning and management of groundwater, particularly in areas where it is closely interrelated with surface water and resources have been allotted to the limit of over-extraction (Hanson and Dettinger 2005).

An estimation of the economic impact of the ongoing presence of the 80 Effect can be seen in the cost of a Public Offer of Water Rights Acquisition (OPAD, its acronym in Spanish) implemented by the CHJ in 2007 and 2008. The aim was to reduce irrigation usage in order to improve the river's volume by acquiring water usage rights from farmers. To do so, they first determined the cost in euros for each cubic metre of irrigation water in representative regional crops, which gave an average value of 0.19 €/m^3. The 2007 OPAD resulted in a water savings of 38.1 Mm^3, a volume similar to that caused by the 80 Effect (30.9 Mm^3/year) at an approximate cost of 3.5 M€ that year. In total, water rights covering 56.8 Mm^3 were purchased from farmers for a total of 5.34 M€.

Given the potential long-term permanence of the rainfall amounts characterizing the 80 Effect, let us extrapolate the OPAD's experiment on aquifer withdrawals to 2027 (end date of the planning horizons proposed by the Water Framework Directive). At the current extraction rates, reserves would fall dramatically, with a resulting economic repercussion that can be calculated at 21.7 to 34.9 M€ (Table 2)

Table 2 Variation in storage volumes assuming the ongoing nature of the 80 Effect over time and its economic implications applying the OPAD's 2007 estimate. Public Offer of Water Rights Acquisition (OPAD, its acronym in Spanish)

Period 2008–2027	Storage deficit Mm^3	Storage deficit Mm^3/year	Total cost M€	Cost due to the 80 Effect M€
Abstractions 250 Mm^3/year	1,278	71	145	21.7
Abstractions 300 Mm^3/year	1,800	100	203	30.4
Abstractions 350 Mm^3/year	2,065	115	233	34.9

5 Summary and Conclusions

The groundwater model flow simulates the evolution of MOS groundwater reserves due to climatological fluctuations (80 Effect) that would otherwise remain masked by abstractions. It has also revealed that this drought cycle has so far caused a recharge deficit in the MOS of 18.9 Mm^3/year compared to the average from 1940–2008, which amounts to a storage change of 509 Mm^3 for the period of 1980–2008. This, in turn, has resulted in a loss of base flow in the Júcar River of 22 Mm^3/year.

From the standpoint of sustainability of groundwater resources, the 80 Effect has significantly affected aquifer recharge since effective rainfall represents 75 % of that recharge. However, in the river-aquifer relation, its effects on the volume of flow of the Júcar River is small compared to the impacts of intensive groundwater pumping. In fact, abstractions have produced a total decrease in river flow of 4,363 Mm^3 between 1980 and 2008. In contrast, the 80 Effect has impacted it by 620 Mm^3, that is, only 14 % of the withdrawal impact or 11 % of the average volume of flow that should have been carried by the river. Applying the estimates used by the OPAD, the costs involved in the storage deficit from the ongoing 80 Effect to 2027 can be calculated at 21.7 to 34.9 M€.

Given these data, if global warming continues to accelerate, the decrease in recharge from rainfall will be crucial to managing and planning the system's water resources and future environmental measures.

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