Modelling the effects of climate change and population growth in four intensively exploited Mediterranean aquifers. The Mijas range, Southern Spain.

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Abstract

Groundwater is key to economic growth in the Mediterranean region. This is particularly true of areas such as southern Spain, where aquifers underpin social development by supplying water to a booming tourist industry. Intensive groundwater use raises sustainability concerns, as pumping often exceeds the long-term recharge rate. Climate change and population growth are likely to exacerbate the water supply challenge in the coming years, due to the expected decrease in rainfall and to increasing competition among users. This paper examines some of the main aquifers in the Costa del Sol region, one of Spain's leading tourist destinations, where intensive groundwater extraction has led to water table drawdowns and the desiccation of all major springs. A numerical model was developed and calibrated for the purpose of evaluating the likely evolution of the system in the future. Downscaled scenarios from global circulation models were coupled with population growth forecasts to establish a range of plausible water management scenarios. Given the relatively small size of the aquifers and the limited recharge rate, the current pumping patterns appear unsustainable. Results suggest that drawdowns in excess of 150 meters could take place within the next decade, thus compromising domestic supplies.

Keywords: Groundwater model, Processing Modflow, climate change, future scenarios, karstic aquifer, fisurated flow system

1. Introduction

Climate change represents a major challenge for water management. In the coming decades, the availability of water for humans and ecosystems is likely to experience noticeable changes as a result of shifting rainfall and temperature patterns, as well as to anthropogenic factors (Escribano Francés et al., 2017). Coastal areas are particularly vulnerable to climate change due to a high density of socio-economic activities and human assets (Iyalomhe et al., 2015). This is particularly true of the Mediterranean region, where seasonal demands are significant owing to a booming tourist industry and where groundwater is increasingly relied upon (Rico-Amorós et al., 2009; Custodio, 2017).

A rise of the average temperature and a reduction of total annual rainfall, together with the intensification of extreme events, rank among the most likely effects of climate change in the Mediterranean (IPCC, 2014). In the Iberian Peninsula, rainfall may decrease between 10 and 40 mm per trimester. Furthermore, a 6^{o}C increase of the average temperature by the end of 21st century has been predicted for the southern parts of Spain (Gutiérrez and Pons, 2006; Ruiz Sinoga et al., 2010). Groundwater resources are vulnerable to these changes because a reduction of recharge rates can be expected from decreasing precipitation and increasing evapotranspiration. This could trigger unwanted effects in those areas where aquifers provide the main source of water supply (Pulido-Velazquez et al., 2017).

The above notwithstanding, climate change is largely unpredictable. Hence, there is a need to endow water managers with tools that are sufficiently simple to use on a regular basis, yet accurate enough to underpin decisions (Ammar Aslam et al., 2018). Those that allow for the simulation of different scenarios are particularly interesting in the face of uncertainty, as thinking in terms of scenarios allows managers and stakeholders to evaluate a range of potential problems and means to adapt (Nguyen et al., 2007; Martínez-Santos et al., 2008). This may in turn contribute to mitigate the impacts of climate change by formulating policies that optimize the use of groundwater for humans and natural ecosystems.

Models have been used for a variety of purposes, such as underpinning water planning (Singh, 2014; Hartmann et al., 2014), studying groundwater recharge and the variation of groundwater levels (Meixner et al., 2016; Mani et al., 2016), or evaluating management scenarios (Michael and Voss, 2008; Martínez-Santos and Andreu, 2010; Chandio et al., 2012). Models are not only predictive tools, but also powerful communication devices, able to present results efficiently and in a visually-appealing fashion. This implies that they can be used at most stages of the planning and management processes.

Developing distributed models presents some difficulties. A large volume of data is needed for calibration and simulations. Understanding geology is particularly important. For instance, carbonate aquifers can be highly heterogeneous, and often present a transition from diffuse Darcian flow (primary porosity) to fracture and conduit flow (secondary and tertiary porosity) (Kaufmann and Braun, 2000). Turbulent regimes are common in karst aquifers, and may be problematic when applying numerical codes that assume laminar flow, homogeneous and isotropic media (Karay and Hajnal, 2015). Moreover, mapping conduits poses a challenge.

Modelling packages dealing with conduit flow have yielded good results in well-developed karst systems at local and sub-regional scales (Hill et al., 2010; Gallegos et al., 2013). Nevertheless, in areas where diffuse flow predominates over turbulent flow, such degree of specialization may be unnecessary. It has been demonstrated that the effects of local heterogeneities tend to fade with larger spatial scales, which implies that karst reservoirs may be modeled by assuming equivalent porous media (Scanlon et al., 2003).

The following pages present a modelling-based approach to evaluate the past and future implications of groundwater-based urban supply in the Costa del Sol aquifers (Mijas Range). The Costa del Sol region is one of the leading tourist destinations of the second most visited country in the world. A history of dropping water tables and groundwater overdraft problems suggests that water supply could become a major threat in the mid-term. In this context, the goal of this paper is to present the development and calibration of the most detailed model developed for this area up to this date, as well as to discuss the potential implications of climate change and population growth on groundwater resources. The availability of over four decades of field data provides an added value to the results, as such large datasets are rarely available in groundwater modelling studies. From a methodological standpoint, this research is not only relevant for southern Spain, but also for coastal Mediterranean regions in general, where the drivers and challenges can be expected to be similar (Ertürk et al., 2014; Benabdallah et al., 2017).

2. Site description. Conceptual model.

The Mijas range spans an area of 80 km^2 in the province of Malaga, southern Spain (Fig. 1, Table 1). The topography is abrupt, altitudes ranging between 76 m a.s.l. in the eastern part and 1150 m a.s.l. (Mijas peak) towards the western end. The western side of the range is generally steeper, with gradients in the order of 50% - 60%. In contrast, the eastern area presents gentler slopes (20% - 35%).

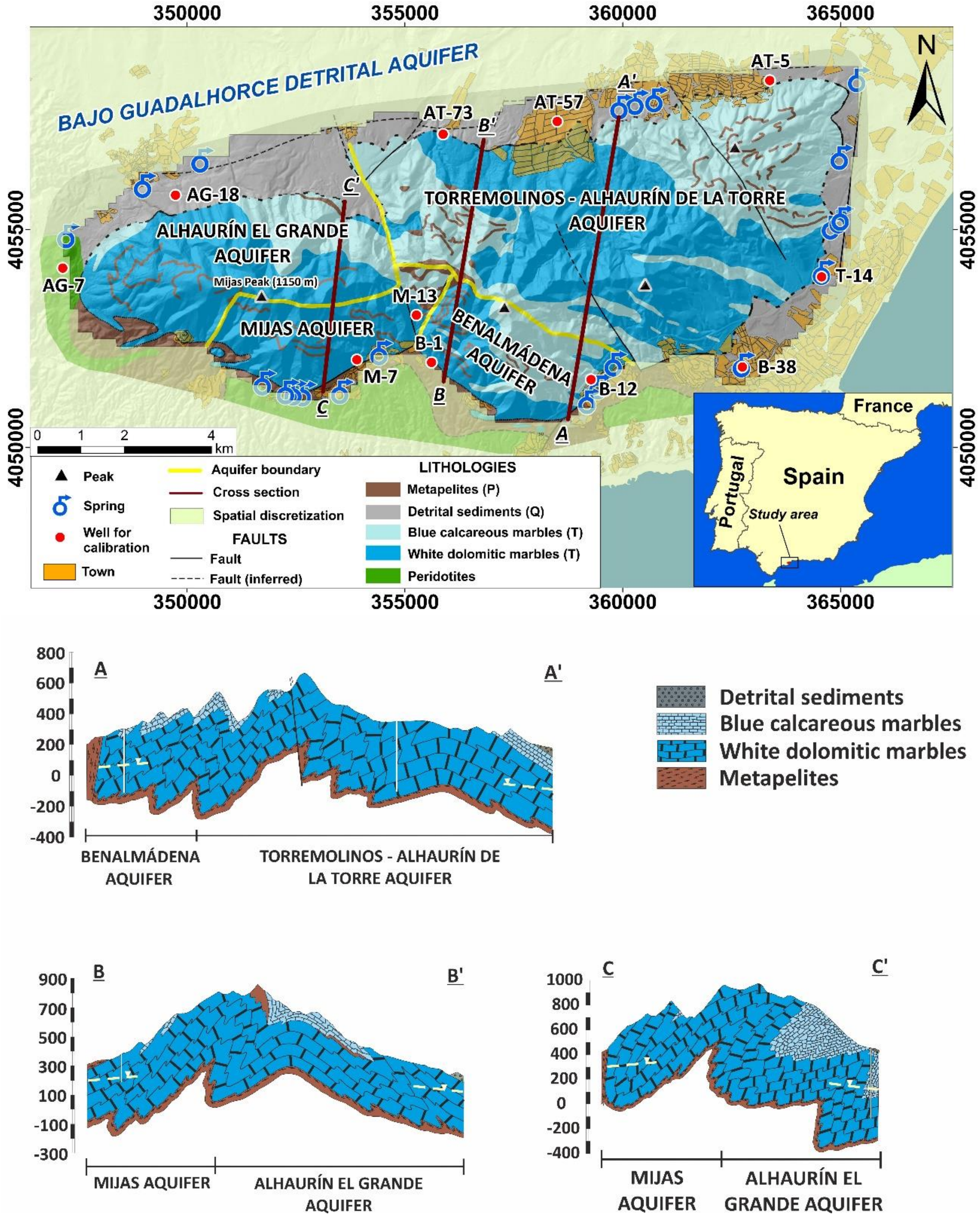

Fig. 1 Location, cross sections and geological map of the study area with the model spatial discretization included

Table 1 Main aquifers features of the Mijas range area

Aquifer / feature	**Surface (km^2)**	**Average modeled thickness**	**Average gelogical modeled paremeters**			**Recharge to pumping historic ratio**	**1990-2015 water table drop rate (m/yr)**
			T (m^2/d)	**Ne**	**S_s (1/m)**		
Alhaurín el Grande	16.7	622.04	175.08	0.013	0.00513	1.35	1.35
Mijas	8.0	445.97	307.90	0.014	0.00066	1.64	3.59
Benalmádena	8.7	512.51	580.69	0.010	0.00046	1.39	6.19
Torremolinos - Alhaurín de la Torre	45.8	490.64	808.96	0.011	0.00457	0.94	4.30

The Mijas range belongs in the Blanca geological unit of the Triassic Alpujarride complex, within the Internal Zone of the Betic Cordillera, southern Spain (Martín-Algarra, 1987). The impervious basement is made up of metapelites (Fig. 1). These are overlain by dolomitic and calcareous marbles. The geological structure is formed by ESE-WNW folds, where the metapelites interrupt the lateral continuity of the marbles in parts of the range (Andreo and Sanz de Galdeano, 1994), thus separating it in four independent aquifers (Andreo, 1996; Andreo et al., 2002): Alhaurín el Grande (surface area = 16.7 km^2), Torremolinos - Alhaurín de la Torre (45.8 km^2), Benalmádena (8.7 km^2) and Mijas (8 km^2). Groundwater flow through the carbonate aquifers largely takes place in a diffuse manner.

From a hydrogeological standpoint, Mijas is limited by faults ENE-WSW, NNW-SSE and NNE-SSW (Fig. 1). Specifically, fractures of the latter two directions and the geological structure influence the compartmentalization and the hydrogeological functioning of the unit (Andreo et al., 1997). The flow regime in the studied area presents a diffuse flow behavior caused by the high degree of fracturation and the low karstification (Andreo et al., 1997; 2002).

The region presents a temperate Mediterranean climate. Hot dry summers follow temperate winters. Rainfall-wise, long dry spells, lasting several years at a time, alternate with short wet periods. The average annual temperature is 18.7ºC, ranging from 12.1ºC in January to 26.3ºC in August. Temperature has been observed to increase gradually since the late 1970s (Fig. 2). The average annual rainfall for the 1964/65-2015/16 period was 649 mm, although there is a clear spatial gradient: rainfall amounts to 710 mm/year in western Mijas village, and to 585 mm/year in Torremolinos village. Rainfall mainly takes place between October and February (71.4%).

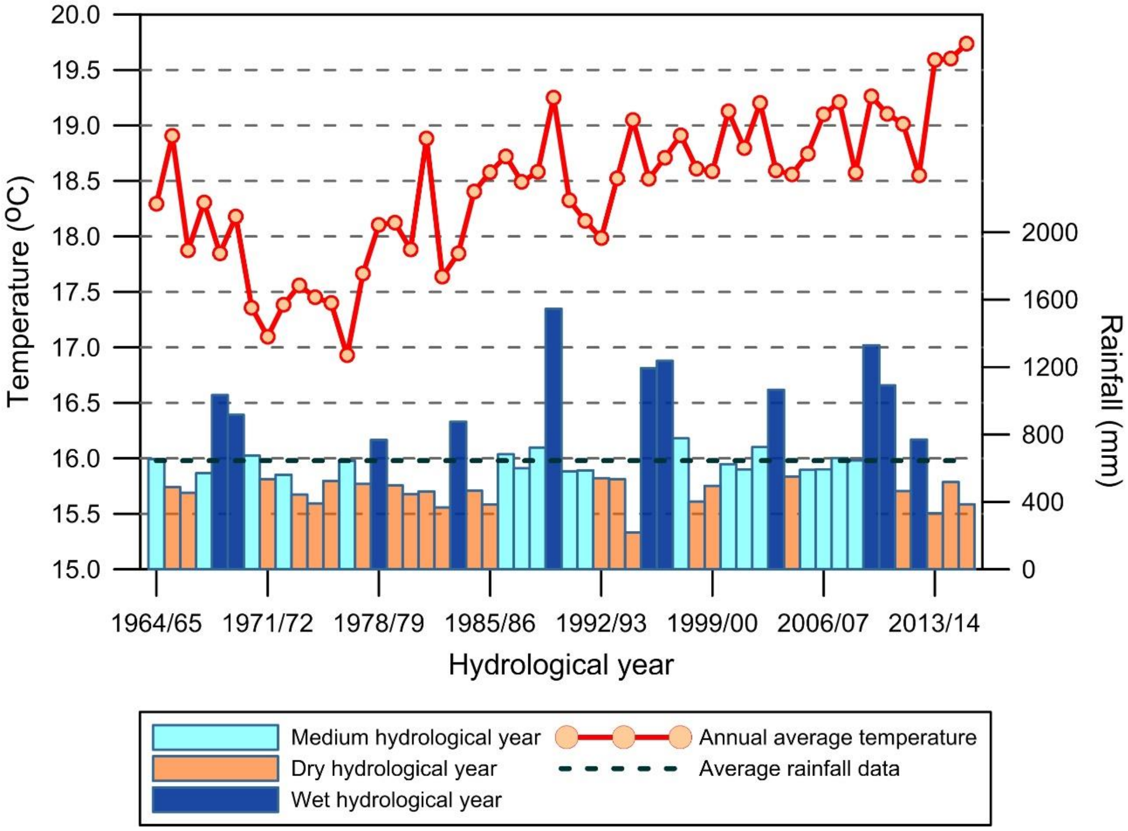

Fig. 2 Temperature and rainfall data in 1964/65 – 2015/16 hydraulic years' period

Surface runoff is largely negligible (Andreo, 1996). Aquifer recharge takes place through direct rainfall infiltration. Natural discharge occurred through twenty-three springs distributed around the boundaries of the range (Fig. 1). Also, a limited volume of water discharges laterally into the Bajo Guadalhorce detrital aquifer. From 1975, groundwater extraction began to offset spring flows, to the point that all springs are now permanently inactive.

From the point of view of water management, the range is divided in two areas: The north side is located in the I-4 sub-system of the Andalusian Water Management Office, whereas the south area is found in the I-3 management sub-system.

Pumping has altered the balance to a different extent in each aquifer (Table 1). The Alhaurín el Grande aquifer traditionally presents the lowest pumping rate (Andreo, 1996), which translates into a lesser perturbation of the natural piezometric surface (Fig. 4). In contrast, the Mijas, Benalmádena and Torremolinos - Alhaurín de la Torre aquifers are subject to intensive extractions. All four aquifers are geologically isolated from the sea.

Currently, all neighboring municipalities rely on groundwater for urban supply. Urban supply is, in fact, the main water user across all four systems (32 hm^3 in 2015/16). Agricultural uses are comparatively small (2.6 hm^3 in 2015/16) and restricted to the northern and western sides of the range.

The Alhaurín de la Torre and Alhaurín el Grande towns, located in the north of the area, rely exclusively on Mijas groundwater for domestic supply. Most of the irrigation water in the agricultural areas also relies on the aquifer. The Mijas, Benalmádena, Torremolinos and Churriana neighborhoods also rely on wells, but could obtain drinking water from other sources, including the Marbella desalination plant and the Concepción reservoir (Argamasilla-Ruiz, 2017).

3. Methodology

3.1. Development of the numerical model

Processing Modflow 8.042 (Chiang, 2012) was used to develop the numerical model. Although it assumes Darcy's law to hold, it provides acceptable results in systems where turbulent regimes take places, like karstic or fractured rocks, where a diffuse flow exists, if primary porosity predominates and/or if the scale is sufficiently large to neutralize the effects of localized flow (Scanlon et al., 2003; Martínez-Santos and Andreu, 2010; Karay and Hajnal, 2015). Both conditions could be assumed valid in this case caused by the regional scale and the hydrogeological behavior of the study area characterized as diffuse flow systems by Andreo et al. (1997; 2002).

The grid consists of 4935 cells (2975 active and 1960 inactive), distributed in 47 rows and 105 columns. Cell size is 175x175 m throughout. Both types of marbles have been modelled as a single permeable layer. The elevation of the aquifer bottom (the top of the metapelite formation) was obtained by geostatistical techniques, based on twelve geological cross sections (Fig. 1). The topographic surface is the top of the permeable layer.

A Neumann boundary condition (no-flow) was used to delineate the limits of the aquifer. These consist on faults and stratigraphic contacts with low-permeability formations (Fig. 1), as well as the limits between aquifer systems. A time-variant specified flow condition was used for recharge and groundwater extractions. Recharge values are uniform in space but different for each aquifer unit, as calculated by means of soil water balances. Data from seven weather stations was used for this purpose (Martín-Arias et al., 2017). Evapotranspiration was calculated by six different methods, including Kessler, Chloride Balance, APLIS (Andreo et al., 2008; Marín, 2009), Thornthwaite, Hargreaves and

Blaney-Criddle. Field capacities of 25 mm and 50 mm were considered for the latter three methods. The outcomes suggest that recharge ranges between 41% (Chloride Balance method) and 72% (Thornthwaite method with a 25 mm field capacity). The Hargreaves infiltration coefficient with 50 mm of field capacity (recharge rate 54% of rainfall) was concluded to be the most suitable during the calibration process. Irrigation return flows and allogenic recharge are both assumed negligible.

A well condition was assigned to the cells where pumping wells are located. Pumping data was facilitated by public supply companies and irrigation communities. Gaps are observed in some years, so they were completed by extrapolating the existing data based on information provided from water supply companies. Data from over 41 pumping tests allowed for an estimation of specific yield, which was established, on average, at 1% (Andreo, 1996).

A Cauchy condition (drain) was used to simulate the springs located around the study area and the lateral groundwater discharge towards the Bajo Guadalhorce aquifer (Andreo, 1996). Spring elevations were established by means of 1:10,000 cartographies (IGN, 2015). Drain hydraulic conductance was adjusted during the calibration process.

Figure 3 presents the structure of the modelling framework. A steady-state simulation was carried out first in order to represent the natural conditions of the system, as well as to establish the initial heads for the transient-state model. The latter comprises 436 monthly stress periods, spanning the 1979-2015 period.

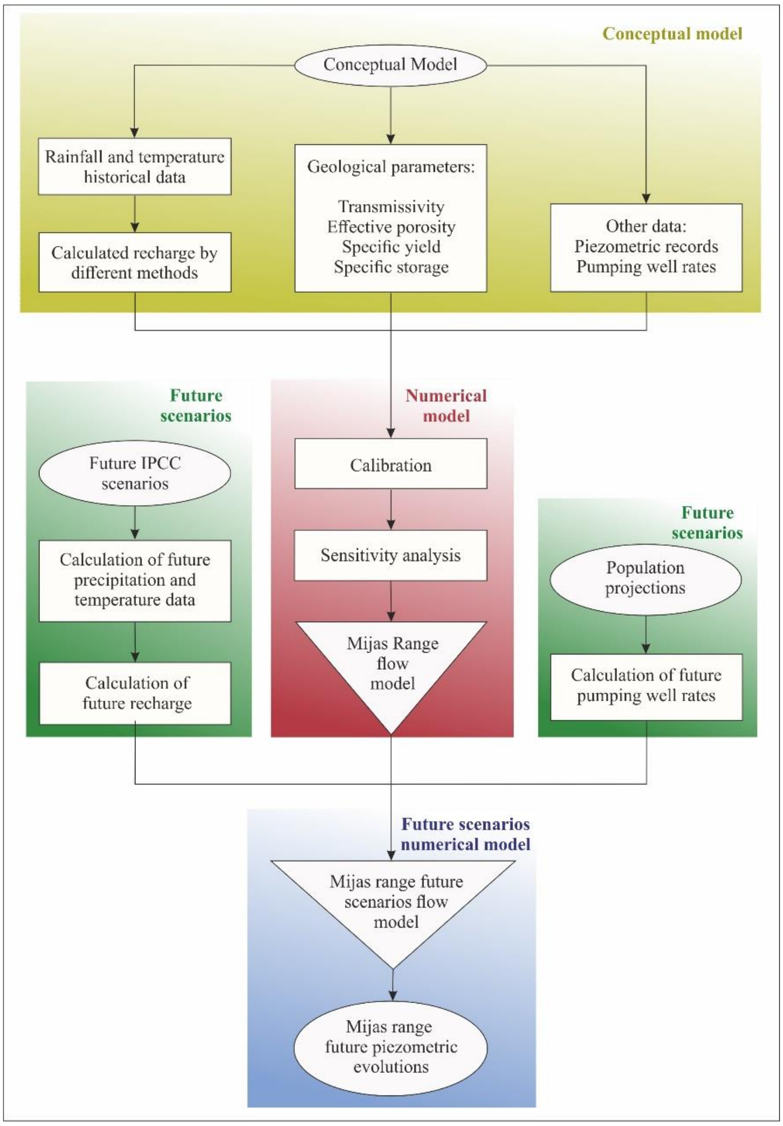

Fig. 3 Flowchart of the modelling framework

3.2. Scenario development

The purpose of modelling scenarios is to evaluate the likely evolution of the water table under a wide range of conditions. The underlying assumption is that the groundwater level will ultimately be controlled by climate and population growth. Climate, –more specifically climatic change–, can be expected to alter the main source of aquifer replenishment, i.e. rainfall, thus modifying the natural component of the water balance. On the other hand, population growth will largely determine urban water demands, that is, how much water will be pumped from these aquifers in the future.

The Andalusian Government downscaled the scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) for the study area (IPCC, 2014; CMAOT, 2014). These suggest an overall reduction of rainfall and an increase of temperatures by the end of the 21st Century. Since both variables ultimately constrain groundwater recharge, they were used to compute monthly aquifer replenishment rates for the simulation period. Recharge predictions rely on a soil water balance that considers a field capacity of 50 mm and evapotranspiration rates computed as per Hargreaves' method. These were extrapolated from 1964-2015 data. Table 2 presents the expected changes in annual rainfall by 2099. These have been obtained from four global circulation models (GCM) and three emission scenarios (SRES) (CMAOT, 2014), parameters used to develop futures scenarios by the international community (IPCC, 2014). As shown, rainfall can be expected to drop between 14.4% in the best-case scenario and 26.6% in the worst.

Table 2 Rainfall forecasts for the Andalusia Region according to four global circulation models (GCM) and three reports on emission scenarios (SRES). Rainfall data in mm/year. Data obtained from CMAOT (2014)

GCM	SRES	PERIOD				DIFFERENCE 2000-2099	% 2000-2099	DIFFERENCE 2000-2040	% 2000-2040
		1961-2000	2011-2040	2041-2070	2071-2099				
CNCM3	A1b	589	573	494	478	-111	-18.8	-16	-2.7
	A2		564	476	477	-112	-19.0	-25	-4.2
	B1		524	538	497	-92	-15.6	-65	-11.0
BCM2	A1b		537	484	450	-139	-23.6	-52	-8.8
	A2		524	469	432	-157	-26.6	-65	-11.0

	B1	549	471	501	-88	-14.9	-40	-6.8
ECHAM5	A1b	545	482	484	-105	-17.8	-44	-7.5
	A2	506	517	442	-147	-25.0	-83	-14.1
	B1	552	524	492	-97	-16.5	-37	-6.3
EGMAM	A1b	520	511	483	-106	-18.0	-69	-11.7
	A2	510	481	508	-81	-13.8	-79	-13.4
	B1	565	517	504	-85	-14.4	-24	-4.1

Table 3 presents the 2015 population census, as well as the 2015-2035 population growth forecasts (IECA, 2013; INE, 2018). Population can be expected to increase by 2035 in all cases. Mijas and Alhaurín de la Torre exhibit the highest growth rate (28.9 and 16.6%), respectively, while Torremolinos is expected to remain around 7.5%.

Table 3 Current population and estimated population growth in the main municipalities supplied by the Mijas range (2015-2035)

Municipality	Population (2015)	% Population growth (2015 to 2035)
Alhaurín de la Torre	38,523	16.6
Alhaurín el Grande	24,338	10.4
Mijas	79,483	28.9
Benalmádena	66,598	10.9
Torremolinos	67,492	7.5

Official reports suggest that the CNCM3 GCM and A1b SRES may be more representative than the others (CMAOT, 2014). Hence, these have been taken as the reference for modelling purposes. SRES A1b, A2 and B1 have been used as emission scenarios for CNCM3 GCM. The expected rainfall reduction in all three SRES used in all GCM were similar. Consequently, only the CNCM GCM scenarios were modelled.

4. Results

4.1. Model calibration

4.1.1. Steady-state calibration

The first pumping wells of the Mijas range were drilled in the 1970s, and began operating immediately. In contrast, the earliest piezometric records stem from 1979. This means there is no water table map depicting the system's natural conditions. For calibration purposes, steady-state results were compared to the next best approximation, that is, 1990. Although by then the system had already experienced some depletion, this date corresponds to the end of an extraordinarily rainy period. Thus, it presents the highest water table elevation on record, which is the closest it has ever come to natural conditions after the 1970s. At this time, springs also became active after many years. Thus, piezometric logs were complemented by spring flow data, which contains some sporadic measurements prior to 1970.

The steady-state model also served the purpose of adjusting hydraulic conductivity. This variable was initially computed from transmissivity values of 41 pumping tests scattered around the study area (Andreo, 1996). Kriging was used to extrapolate the existing data to the entire grid.

4.1.2. Transient-state calibration

The transient-state model was calibrated for the 1979-2015 period, with data from 11 representative boreholes (Fig. 1). Inverse calibration was used to determine the best fit between field data, recharge and the hydrodynamic parameters. Fitted parameters were all kept within the limits of plausibility, based on the available field information.

Groundwater data was collected from a variety of sources, including water supply companies, water authorities and the Geological Survey of Spain. The existing records present two shortcomings. On the one hand, many of the piezometric logs were incomplete. This is perceived to be a minor inconvenience, since all series exceed fifteen years (Fig. 4). On the other hand, it was observed that groundwater levels have sometimes been collected under dynamic conditions, which implies that the calibration is best interpreted at the trend scale.

Historical records were also available for some of the main springs. The longest ones correspond to the Torremolinos springs, as well as to one spring in Alhaurín el Grande. All spring records end in 1995, the year in which discharge took place for the last time.

Fig. 4 show the long term calibration results of the system in four representative observation wells and the steady and transient-state calibration of the model, respectively.

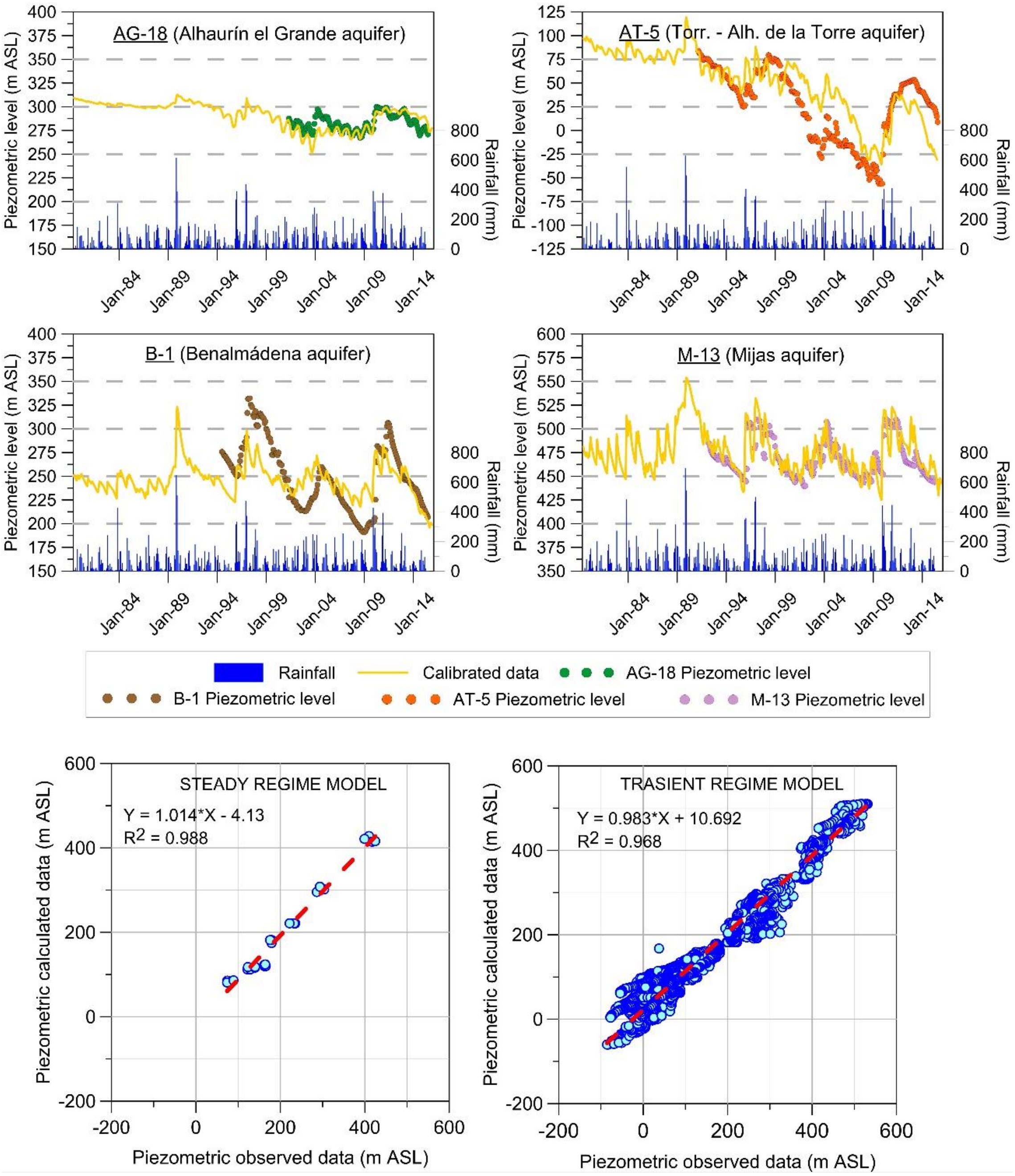

Fig. 4 Calibration results for four representative observation wells (AG-18, B-1, AT-5 and M-13) and correlation between calculated and observed values under steady- and transient-state conditions

The root mean square error (RMSE) and the mean absolute error (MAE) have been calculated to evaluate the calibration. RMSE and MAE were, respectively, 12.0 m and 10.1 m for the steady-state model; and 27.8 m and 19.3 m for the transient model in all 15 calibration points. This information, combined with the piezometric evolution in Fig.

4, suggests that the model is reliable at the trend level. However, it also implies that the model is not necessarily accurate at predicting the water table elevation for a specific moment in time. This limitation cannot be overcome without more detailed field data, but the accuracy of the model at trend level is considered sufficient for the purpose of this work.

4.1.3. Sensitivity analysis

A sensitivity analysis was carried out for the more uncertain parameters, namely recharge, hydraulic conductivity and specific yield. In the case of hydrogeological parameters, uncertainty stems from spatial heterogeneity. This is particularly true of those carbonate aquifers where diffuse flow predominates. Moreover, the interpretation of pumping tests is rarely univocal. As a result, hydrodynamic variables are often presented as a range rather than as clear-cut values. This is relevant to the modelling process because small changes in one of these variables may have a significant bearing on the results. An added difficulty in the case at hand is that the vast majority of the 41 pumping tests have been carried out in the flatter sectors of the range (i.e. the boundaries), while little pumping-test information is available in the central part of the range. This owes to the fact that the more abrupt areas are unsuitable for drilling and operating water supply wells.

Aquifer recharge is naturally difficult to estimate. This is largely because the interactions between surface and groundwater are naturally complex and dependent on a variety of climatic, geological and biotic factors. Thus, the strategy in this case was to test different methods to establish a sufficiently plausible range of recharge values.

In the case of recharge, the sensitivity analysis was performed first by keeping the best-fit hydrodynamic parameters fixed and testing all five recharge estimation methods. A similar approach was carried out with the hydrodynamic parameters, fixing recharge first and then carrying out several model runs under different combinations of hydraulic conductivity and specific yield (Fig. 5).

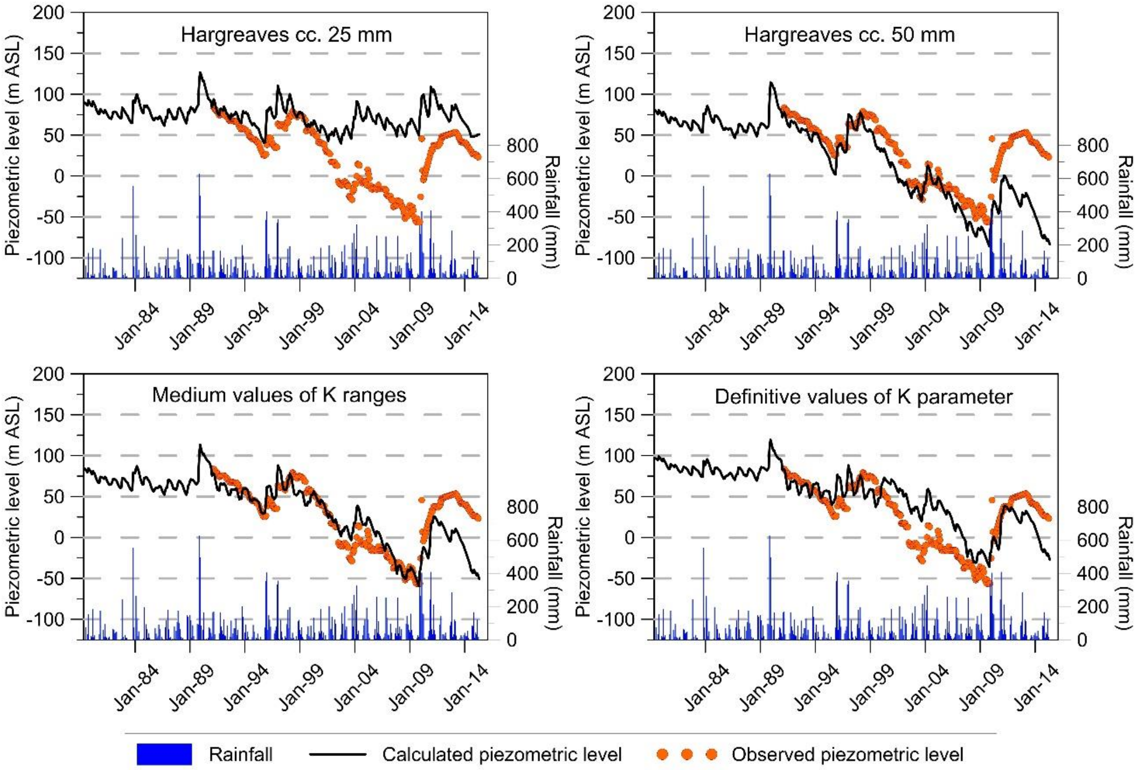

Fig. 5 Sensitivity analysis for recharge and hydraulic conductivity parameters at observation well AT-5 (Torremolinos – Alhaurín de la Torre aquifer). Transient-state conditions

Table 4 Sensitivity analysis for selected parameters (T = transmissivity, S = specific yield, R = recharge, Ne = effective porosity)

Test variable (test value)	**Fixed variables (adjusted value)**	**Calculated vs Observed (R2)**	**Calculated vs Observed (Kling-Gupta)**	**Root Mean Squared Error - RMSE (m)**
S (/2)	Ne, R, T	0.967	0.923	28.52
S (/10)	Ne, R, T	0.963	0.932	31.44
S (/100)	Ne, R, T	0.954	0.928	35.43
S (X2)	Ne, R, T	0.969	0.844	33.69
S (x10)	Ne, R, T	0.955	0.765	48.53

S (x100)	Ne, R, T	0.952	0.754	51.86
Ne (/2)	S, R, T	0.926	0.869	52.93
Ne (/10)	S, R, T	0.586	-3.759	383.17
Ne (/100)	S, R, T	0.349	-0.522	4161.85
Ne (x2)	S, R, T	0.970	0.842	33.70
Ne (x10)	S, R, T	0.955	0.784	45.90
Ne (x100)	S, R, T	0.949	0.758	52.15
R (APLIS)	S, Ne, T	0.904	0.829	65.71
R (Blaney Criddle, 25 mm - monthly)	S, Ne, T	0.955	0.782	48.89
R (Blaney Criddle, 25 mm - daily)	S, Ne, T	0.970	0.898	27.42
R (Blaney Criddle, 50 mm - monthly)	S, Ne, T	0.968	0.907	27.96
R (Blaney Criddle, 50 mm - daily)	S, Ne, T	0.911	0.861	59.05
R (Hargreaves, 25 mm - monthly)	S, Ne, T	0.955	0.782	48.97
R (Hargreaves, 25 mm - daily)	S, Ne, T	0.973	0.925	29.70
R (Hargreaves, 50 mm - monthly)	S, Ne, T	0.969	0.970	27.83
R (Hargreaves, 50 mm - daily)	S, Ne, T	0.944	0.951	39.86
R (Thornthwaite, 25 mm - monthly)	S, Ne, T	0.955	0.782	49.16
R (Thornthwaite, 25 mm - daily)	S, Ne, T	0.966	0.811	40.25
R (Thornthwaite, 50 mm - monthly)	S, Ne, T	0.973	0.907	32.65
R - (Thornthwaite, 50 mm - daily)	S, Ne, T	0.973	0.882	27.86
T (min) (/10)	S, Ne, R	0.913	0.935	48.12
T (min)	S, Ne, R	0.903	0.883	56.51
T (avg)	S, Ne, R	0.721	0.750	110.18
T (max)	S, Ne, R	0.856	0.653	77.53
T (max) (x10)	S, Ne, R	0.916	0.937	47.05

Table 4 shows the results of the sensitivity analysis. Overall, the best adjustment between observed and calculated levels was found for the recharge estimate obtained by applying Hargreaves' evapotranspiration method (field capacity 50 mm and monthly rainfall data), with a coefficient of determination and a Kling-Gupta efficiency coefficient of 0.969 (Table 4) and 0.970, respectively. However, the sensitivity analysis reveals that the model is largely insensitive to changes in recharge rates. In contrast, a decrease of one order of magnitude in hydraulic conductivity renders a comparatively poor adjustment, whereas the model fails to converge after 365 time steps for the same modification in specific yield. Moderate to large increases in both hydrodynamic parameters do not have a strong bearing on the adjustment.

4.1.4. Water budget

Table 5 presents the steady-state water budget for all four aquifers. Direct infiltration is the sole inflow in all cases. Spring discharge is the main outflow mechanism, but it differs in importance from one system to another. Lateral discharge into the Bajo Guadalhorce detrital aquifer is either zero or negligible for practical purposes. Lateral transference through the northern limit of Torremolinos – Alhaurín de la Torre aquifer has been calculated on the order of 1 hm^3/year in other studies (Andreo, 1996).

Table 5 Water budget under steady-state conditions (hm^3/year)

AQUIFER	OUTFLOWS		INFLOWS
	SPRINGS	LAT. TRANSFERENCE	RECHARGE
Alhaurín el Grande	5.49	0.00	5.49
Mijas	3.18	-	3.18
Benalmádena	3.28	-	3.28
Torremolinos - Alhaurín de la Torre	16.25	0.43	16.68

Fig. 6 shows the yearly evolution of inflows and outflows as per the results of the calibrated model. Spring discharge is observed to gradually disappear under perturbed conditions in all four aquifers, with the exception of some sporadic events. These are closely associated with major recharge episodes. In contrast, groundwater pumping increases more or less steadily over time across all systems, with Torremolinos – Alhaurín de la Torre aquifer as the most intensively exploited.

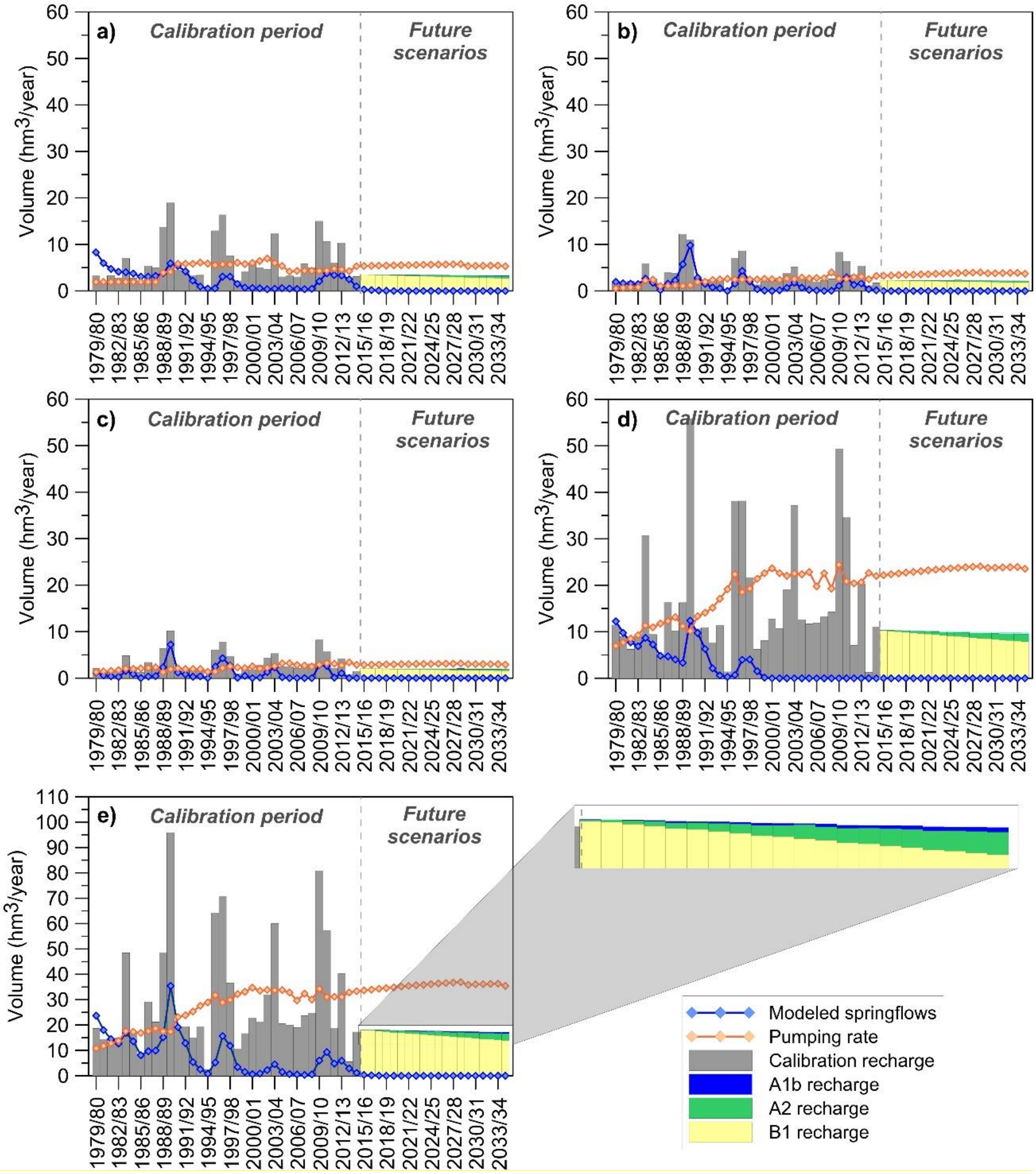

Fig. 6 Water budget evolution over time at (A) Alhaurín el Grande, (B) Mijas, (C) Benalmádena, (D) Torremolinos - Alhaurín de la Torre aquifers, and (E) the whole system. The graphs include the simulated evolution for all three future scenarios

4.2. Scenario simulation

All simulations consider horizon 2035, and use the emissions scenarios from the CNCM3 global circulation model. Fig. 7 presents the water table evolution at a series of representative observation wells distributed across all four aquifers.

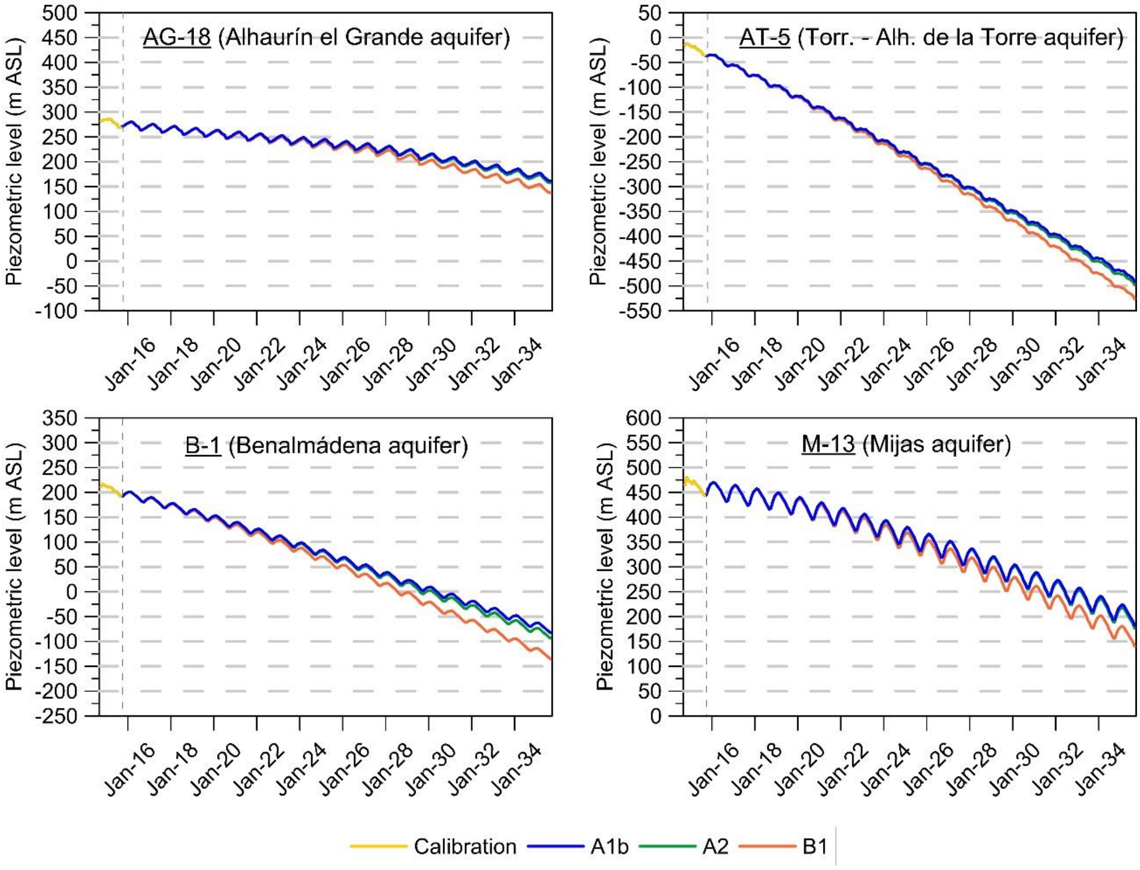

Fig. 7 Results of scenario simulations at observation wells AG-18, B-1, AT-5 and M-13

Scenarios A1b and A2 provide similar results, while B1 predicts an overall greater decline. Simulations also reveal two clear trends. Drawdowns are likely to be more acute in the Torremolinos - Alhaurín de la Torre aquifer, where a drop in excess of 100 meters could take place in all modelled scenarios (Fig. 7). Mijas, Benalmádena and Alhaurín el Grande models suggest that levels will decrease slowly. The lowest piezometric decrease has been calculated in Alhaurín el Grande aquifer. This is because the pumping rate in relation to the size of this unit is comparatively smaller than the others.

5. Discussion

5.1 Practical implications of modelling results

Spain was the second most visited country in the world in 2015 and 2016, ranking only behind France (UNWTO, 2017). Tourism currently represents 16% of the national gross domestic product, generating millions of direct and indirect jobs. The Costa del Sol, which ranks among Spain’s top five tourist regions, provides an excellent example. Fueled by iconic destinations such as Marbella, Malaga or Torremolinos, the regional population increases two-fold during the high season. This presents important implications for water resources management, as tourist water demands are considerably higher than the local ones due to the widespread use of swimming pools and green areas (Thot et al., 2018; Gössling et al., 2012). In addition, the resident population is expected to increase in the coming years. Official forecasts suggest that all municipalities in the study area will grow by 2029 (IECA, 2013; INE, 2018).

The importance of the Mijas aquifers cannot be overstated, as it represents the main source of water supply for these municipalities (Andreo, 1996; Martín-Arias et al., 2016). Long-term piezometric logs reveal a downward trend in most cases, with a decline in the order of 30-50 meters in three out of the four aquifer units over the last two decades. Even if a sustained decline of the water table does not constitute an unequivocal symptom of aquifer overdraft (Martínez-Santos et al., 2018), the current state of affairs questions whether pumping patterns can be maintained in the mid to long term. Furthermore, climate change can be expected to result in less water and increasing competition among users, thus exacerbating water supply challenges.

In the case at hand, levels are likely to continue falling due to the joint effect of increased pumping and decreasing groundwater recharge. This is consistent with estimates for other parts of southern and eastern Spain. For instance, Aguilera and Murillo (2008) found recharge in four overexploited karst aquifers in Vinalopó area (Alicante, SE Spain) to have fallen by over 50% in the 20th century. Touhami et al. (2015) carried out a prediction for recharge in the same area for the 2011-2099 period, using an A2-high and B2-low scenario and HadCM3 GCM. These authors concluded that recharge could be expected to decrease between 3% and 17%, in relation to the baseline period (1961-1990). The impact of climate change on recharge has also been modeled in Majorca, where the decrease in natural recharge would be reduced from 4% to 21% by 2025, compared to 1980-2005 period. This estimate considers HadCM3 GCM, in scenarios B2 and A2, respectively (Candela et al., 2009). In the Almonte-Marismas aquifer, the reduction in mean recharge will range from 14% to 57% by the 2080s, compared to 1961-1990 period, in the A2 scenario and depending on the GCMs considered (CNCM3 and HADCM3 or NCPCM) (Guardiola-Albert and Jackson, 2011).

Involving water managers in modelling exercises is desirable because they can validate the results and provide a practical outlook (Zorrilla et al., 2009). This research was commissioned by the local water supply companies in an attempt to evaluate the vulnerability of the existing resources to the main drivers for change. In their view, the outcomes suggest that there is a need to optimize groundwater use, to improve the efficiency of distribution systems and to develop alternative water sources.

For practical purposes, there are only two means to prevent piezometric decline in the study area. The first one is to optimize groundwater use. Steps have been taken to improve efficiency in the southern part of Mijas range, leading to a 15% reduction of groundwater pumping in Torremolinos between 2010 and 2015. The second approach would be to develop alternative sources. Desalination could provide a welcome complement to groundwater extraction. For instance, Marbella’s desalination plant (45 km to the east of the Mijas range) currently provides drinking water to some of the southern municipalities. However, the high cost of desalinated water seems to represent an incentive to maintain the groundwater pumping (Argamasilla-Ruiz, 2017). Surface water reservoirs, such as Concepción Dam, could also be used. Nevertheless, the reservoir is managed by an external company and the taxes to use this source of water in the Mijas range area are unsuitable for the companies of water management. Thus, further work is needed to determine the extent to which these solutions would be able to stabilize the water table, or even to restore the springs and their associated ecosystems to natural conditions.

5.2 Model limitations and the way forward

Numerical modelling is adequate technique simulate the evolution of complex natural systems (Singh, 2014). However, it also holds true that models depict reality in a simplified manner. Thus, model outcomes should always be understood as estimates and handled with care.

At times, the process of developing a model can be more important than the model results, for it may raise important practical questions. In this case, deficiencies were observed within the existing hydrogeological information. For instance, there is no actual evidence as to where the bottom of the aquifers is, as none of the 41 existing boreholes (some of which exceed 200 meters), reach the impervious basement. Thus, its elevation could only be inferred indirectly, based on the interpretation of the structural geology (Andreo and Sanz de Galdeano, 1994). Clarifying the geometry of the system is important in view of the expected piezometric evolution, as the resource is obviously finite. Furthermore, the vast majority of the pumping wells are located near the borders of the system, which implies that there is relatively little knowledge as to the hydrodynamic parameters in the central part of the range. All this leads to the conclusion that there is room for improvement in terms of hydrogeological knowledge. It also means that, even though the model is reliable enough for practical purposes, its results could be further qualified by new geological evidence.

Scenario modeling is more of a means to think about the potential outcomes of current actions than an attempt to “guess” what will actually happen. By developing storylines as to how the future may unfold, scenarios allow us to gain insights regarding current strategies. This allows water managers to plan in terms of the range of situations they may face in the future, and act accordingly (Ertürk et al., 2014; Nkhonjera and Dinka, 2017). Thus, even if it is recognized that there are issues of linearity both in climate change and population growth predictions, the key lessons to draw from this study are that: (a) the water table is likely to continue dropping in all four aquifers; (b) the recovery of springs is highly unlikely; (c) water supply costs are likely to increase; and (d) climate change can be expected to result in increased competition between uses.

6. Conclusions

This paper has presented a modelling approach to estimate the effects of climate change and population growth at a major tourist destination in southern Spain. A distributed model was applied to simulate the evolution of groundwater levels in the four aquifers of the Mijas range, which supplies drinking water to the local and seasonal population. Diffuse flow through highly fissured media taking place in certain parts of the system was successfully simulated by means of an equivalent porous medium. Acceptable calibration and input coefficients suggest that this can be an acceptable course of action in aquifers subject to a mixture of turbulent and laminar flow.

Three management scenarios were developed and tested for the 2016-2035 interval. Outcomes suggest that declining piezometric trends are unlikely to be reversed in the future. This is attributed to the joint effect of an expected reduction in aquifer recharge and mounting groundwater demands. These findings are consisting with those obtained in other areas of the Mediterranean, thus raising sustainability concerns for the future. Integrated management of different freshwater sources, including surface water and desalination and reuse, is advocated as a means to prevent water supply shortages in the mid-term.

Acknowledgements

This paper was funded under projects 8.06/5.44.4100 of the University of Málaga, CGL2015-65858R of the Ministerio de Economía y Empresas (MINECO), and the Research Group RNM-308 of the Junta de Andalucía. The authors would also like to thank to water supply companies of Alhaurín de la Torre, Torremolinos and Benalmádena, as well as the farmers and groundwater users of the Mijas range for their cooperation. In addition, the authors would also like to thanks Andreas Hartmann (University of Freiburg, Germany) for his support in the correction of this paper. The paper compiles some of the main results of the first author's Dissertation.

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