

Contribution of decision support systems to water management improvement in basins with high evaporation in Mediterranean climates

Verónica Ruiz-Ortiz, Santiago García-López, Abel Solera and Javier Paredes

ABSTRACT

The entry into force of Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000 established a new model for the management and protection of surface water and groundwater in Europe. In this sense, a thorough knowledge of the basins is an essential step in achieving this European objective. The utility of integrative decision support systems (DSS) for decision-making in complex systems and multiple objectives allows decision-makers to identify characteristics and improve water management in a basin. In this research, hydrological and water management resource models have been combined, with the assistance of the DSS AQUATOOL, with the aim of deepening the consideration of losses by evaporation of reservoirs for a better design of the basin management rules. The case study treated is an Andalusian basin of the Atlantic zone (Spain). At the same time, different management strategies are analysed based on the optimization of the available resources by means of the conjunctive use of surface water and groundwater.

Key words | conjunctive use, decision support systems (DSS), evaporation, reservoir, water resources systems

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INTRODUCTION

Water resources are under increasing pressure associated with population growth, the development of economic activities and the potential scenarios of climate change that predict a significant decrease in precipitation and streamflows (Alcamo *et al.* 2007; González-Zeas 2012). Water resource management includes two basic components and their relationships. On the one hand, the sources of the resource must be managed; on the other hand, water demand must be met. In relation to the latter, irrigated agriculture is the main demand for water, with

consumption of more than 70% of the total freshwater of the world. In fact, in some basins, water management is focused almost exclusively on supplying agricultural demands, as is the case of this study on the Barbate River basin (Cádiz, Spain). Measures aimed at more efficient use of water in agriculture have been developed in recent times. Strosser *et al.* (2007) proposes implementation of a system based on the recovery of the cost of water from the payment of the users. Other measures are aimed at increasing the efficiency of irrigation systems (Singh 2014a), to alleviating the effects of droughts on agriculture (Ghabaei Sough *et al.* 2018) or reducing the soil salinization in arid areas (Li *et al.* 2018).

However, the optimization of water can also be analysed from the point of view of the availability. For

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this, the use of hydrological models, of decision support systems (DSS) or a combination of both (Pedro-Monzonís et al. 2016) are very useful. Singh (2014b) performed an exhaustive compilation of the different studies carried out on computational models for the conjunctive use of water; these extend from the first models (Tyagi & Narayana 1981), whose objectives were to define the amount of surface water and groundwater needed for irrigation, to the most recent (Rezapour Tabari & Soltani 2013; Singh 2014c), in which a very high number of sources and demands are simulated to optimize the resource by means of programming techniques in constant evolution (Condon & Maxwell 2013). Therefore, currently, the DSS are supported by easy-to-use computer software such as AQUATOOL (Andreu et al. 1996), WARGI (water resources system optimization aided by graphical interface) (Sechi & Zuddas 2000) and AQUATOR developed by Oxford Scientific Software in 2001.

Surface water and groundwater are two components that interact according to climatic, terrain relief, geological and biotic factors (Sophocleous 2002). Therefore, an impact on one of them will inevitably affect the quantity and quality of the other (Tanvir Hassan 2014). However, surface water and groundwater have traditionally been considered as two distinct and independent components of the hydrological cycle. In the 1970s, the concept of 'hydro-schizophrenia' appeared, a term proposed to designate the mental separation that people make between the superficial waters (that they see) from the subterranean (that they do not see). Since then, consciousness has developed about the importance of the interactions of these two components of the hydrological cycle to meet human needs, as well as ecological functions in riparian zones and other dependent ecosystems. In addition, current legal regulations such as the Water Framework Directive (EP 2000) have led to a major research activity on issues related to joint management.

This research is part of a project that has the support of the Ecological Transition Ministry (Government of Spain), through the Biodiversity Foundation, in the matter of climate change. Its main objective is to deepen the knowledge of the management of an Andalusian hydrographic basin in the Atlantic zone (Spain) and to analyse the possible management strategies based on the optimization of the available resources by means of the conjunctive use

of surface water and groundwater, helping managers to decide which management is the most suitable. For this aim, the decision support system AQUATOOL and its SIMGES module have been used. As a characteristic element of this basin, the only surface reservoir with multi-annual regulation capacity has a significant loss due to direct evaporation. Therefore, the contribution of the DSS to the quantification of this output of the balance has been analysed, and management alternatives aimed at mitigating this water problem have been proposed.

STUDY AREA

General characteristics of the Barbate River basin

The study area is located on the Atlantic coast of Andalusia (SW Spain). Specifically, it is in the province of Cadiz (Figure 1). The basin of the Barbate River, with a surface of approximately 1,330 km², has a smooth orography for most of its area, mainly with elevations not exceeding 200 m above sea level (a.s.l.), with slopes of less than 3% on average in the lower basin. Nevertheless, in the upper basin, elevations reach 1,095 m a.s.l., and the slopes are quite pronounced.

The climate context is Mediterranean with Atlantic influence. The average annual precipitation is close to 800 mm/year, the average annual temperature is approximately 18 °C, the potential and real evapotranspiration is about 1,110 and 585 mm/year, respectively. On the other hand, the wind is a very characteristic feature of the studied area. The most frequent are the West (Poniente) winds and East (Levante) winds. Poniente winds are moist, fresh and



Figure 1 | Location of the studied area.

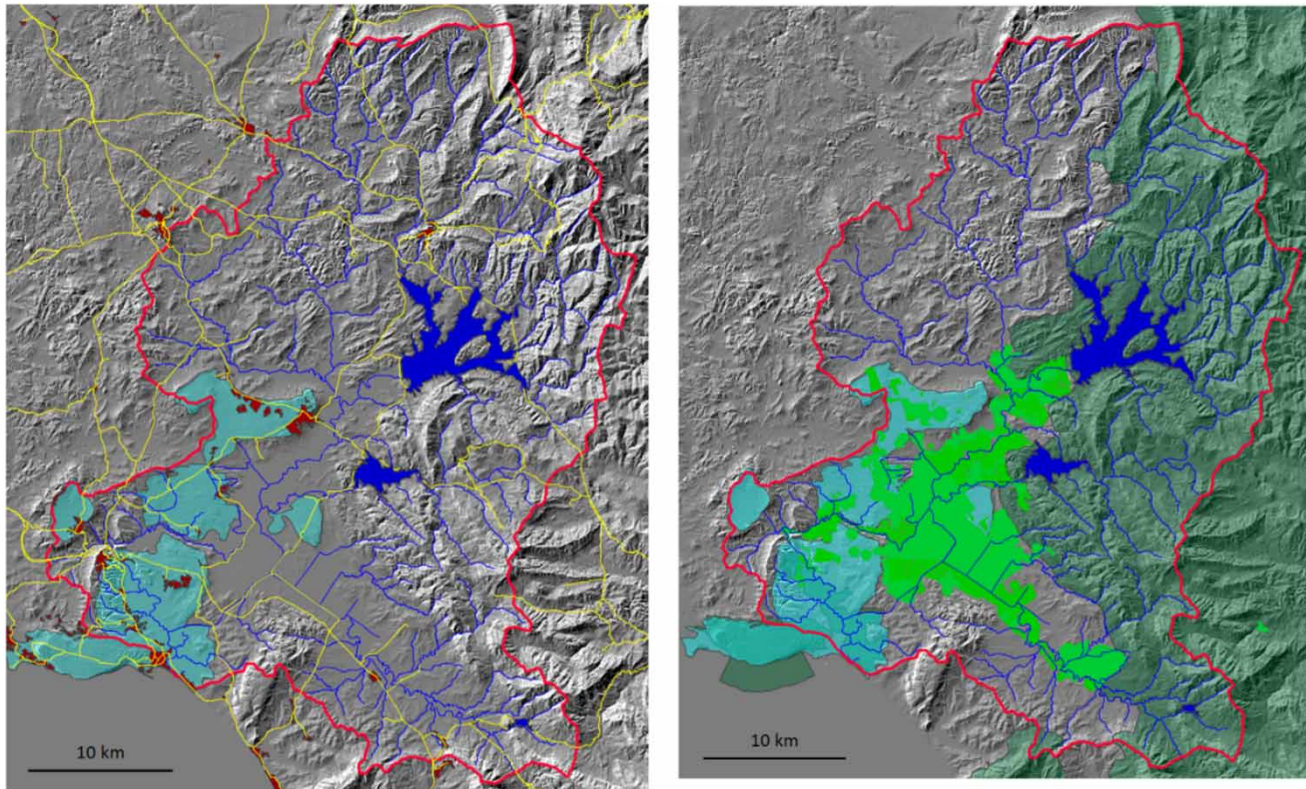


Figure 2 | Left: hydrological elements: hydrographic network, reservoirs and groundwater bodies. Right: location of irrigated farmland and natural parks.

cause precipitation to ascend towards the interior, with the humidity brought from the sea being condensed. However, the Levante winds are warm and dry and can reach speeds of more than 100 km/h.

The main river of the basin is the Barbate River, which originates in the Aljibe Sierra and opens into the Atlantic Ocean. Along its left margins, it receives the Celemín and Almodóvar Rivers. The three rivers are regulated by their homonymous reservoirs: Barbate (228 hm³ capacity), Celemín (45 hm³) and Almodóvar (5.7 hm³). From its right margin, the Barbate River receives the contributions of the River Álamo, without regulation (Figure 2, left). The management of the Barbate and Celemín reservoirs is carried out jointly for the irrigation of 12,230 ha. Almodovar reservoir is multipurpose: water supply (18,000 inhabitants) and irrigation (362.6 ha) (Figure 2, right). Downstream from the reservoirs, the rivers are used as distribution channels to the consuming areas, for which a series of floodgates and pumps have been built to allow water diversion.

In terms of geological characteristics, the Barbate River basin belongs to Gibraltar's flysch unit. At least two independent operating aquifer systems are recognized. The first, identified in the Hydrological Plan (Junta de Andalucía 2016) as a groundwater body (GWB), Benalup (062.014), integrates a single outcrop (33 km² of area) of sand and carbonated calcarenites. This aquifer is in a topographical position several tens of metres elevated over the hydrographic network. The second, with approximately 93 km² of surface, identified as GWB Barbate (062.013), presents several outcrops of permeable rocks (calcarenites, Pliocene sands and Quaternary and alluvial deposits) disconnected at the surface, but they predictably have connection in the subsoil. In the study basin, in addition to the surface infrastructures, many (>200) groundwater catchment wells are present, and these provide water to supply the approximately 9,000 inhabitants and irrigation for approximately 2,500 ha.

Water resources problems of the Barbate River basin

The Barbate River basin presents some specific characteristics that affect the management and exploitation of the water resources:

1. In accordance with the current Hydrological Plan, all groundwater bodies in the basin are classified as being in a bad quantitative state. On the one hand, the piezometric records reflect a temporally descending and prolonged evolution. On the other hand, the index of exploitation (volume extracted/available resources) of the GWB is higher than that established as normative (BOE 2008). In addition, contaminants, mainly nitrates, are present in concentrations higher than recommended. For this reason, the Barbate River basin is also classified as being in a bad qualitative state.
2. The annual average renewable resources in the natural regime of the basin have been estimated at 247 hm³/year, of which 25 are from underground runoff in the middle basin. The annual average demands amount to 102 hm³/year. The WEI (Water Exploitation Index, a quotient between the annual mean extraction of freshwater and the mean long term of the available resource) is used in the study of vulnerability models of water resources. This index determines the water stress in European basins. Alcamo et al. (2000) notes that a result above 20% indicates the presence of water stress and strong competition for more than 40% of the water, with difficulty in maintaining aquatic ecosystems.

Table 2 | Average annual contributions to reservoirs for different lengths of data series

Data period	Data source	Contribution (hm ³ /year)
1940/41–2011/12	PH	135.2
1980/81–2011/12	PH	123.3
1999/00–2015/16	SAIH	119.5

PH, Hydrological Plan of the Guadalete-Barbate; SAIH, automatic hydrological information system.

In the Barbate River basin, the WEI is higher than 40% (Table 1).

In addition, of the estimated superficial contributions (223 hm³/year), only 52% (117 hm³/year) are regulated, so 48% of the superficial contributions are almost entirely carried to the sea. When the contributions of the three reservoirs of the basin are simultaneously analysed, a decrease is observed, depending on the length of the data series considered (Table 2). This could be associated with climate change which aggravates the situation of water stress in the basin.

3. The reservoir with the highest capacity of the system and the only one with a multiannual regulation capacity (Barbate), experiences significant losses due to direct evaporation. The Barbate dam sits on a valley with a very mild morphology. For this reason, the dam has some peculiar characteristics (dike length 1,359 m, dam height 30 m, surface flooded to maximum reservoir 2,540 ha). Moreover, in the study area, a meteorological phenomenon – the East Wind – significantly increases the evaporation. As shown in Figure 3, as the water

Table 1 | General water budget of the Barbate River basin. Determination of the Water Exploitation Index (WEI)

	Element	Data period	Average value hm ³ /year		WEI (%)
Superficial contribution	Barbate reservoir	1999–2016	86.0	222.4	41.1
	Celemín reservoir	1999–2016	25.6		
	Almodóvar reservoir	1999–2016	6.5		
	Álamo River	1980–2011	63.9		
	Ballesteros stream	1980–2011	12.1		
	Low basin	1980–2011	28.3		
Underground contribution	Benalup aquifer recharge	1999–2016	6.8	24.8	
	Lomas aquifer recharge	1999–2016	10.2		
	Vejer aquifer recharge	1999–2016	7.8		
Demand	Urban	1990–2008	2.8	101.7	
	Agricultural	1990–2008	82.0		
	Ecological	1990–2008	16.9		

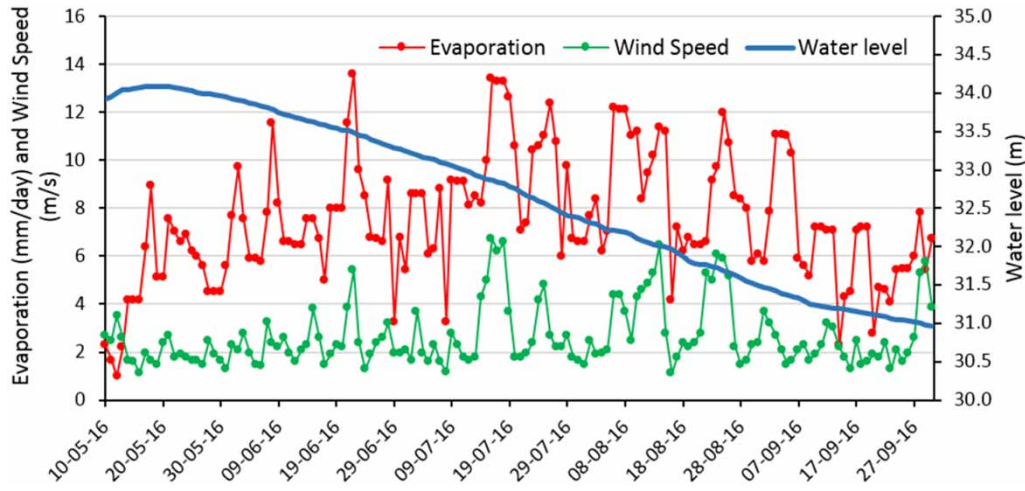


Figure 3 | Daily evaporation evolution, wind speed and water level during the summer of 2016 in the Barbate reservoir.

level in the Barbate reservoir gradually decreases during the summer of 2016, strong evaporation oscillations associated with periods of intense wind are present. This phenomenon doubles the evaporation values achieved of up to $180,000 \text{ m}^3/\text{day}$, compared to the usual ones between $60,000$ and $100,000 \text{ m}^3/\text{day}$.

METHODS

Data collection

For the characterization of the hydrological system of the Barbate River basin, a determination and description of the components and the surface water and groundwater resources, the current and future demands, and the existing hydraulics infrastructures are needed. Therefore, through *in situ* recognition of the basin, extensive databases related to the management of water resources have been obtained. The historical series of the main variables of the three reservoirs of the basin (water inflows, precipitation, water level, water storage, total discharge, discharge for irrigation, discharge for ecological flows) were obtained from the Automatic Hydrological Information System (SAIH) of the Guadalquivir basin, with its corresponding statistical analysis and error detection of the variables recorded. The hydrological statistics for precipitation, evaporation, runoff and infiltration in the aquifers, collected as part of

the Hydrological Plan of Guadalete-Barbate (Junta de Andalucía 2016), were analysed. These variables have been calculated as part of a long historical series (1940/41–2011/12) and short series (1980/81–2011/12) from the data of the model of Precipitation-Streamflow SIMPA (integrated system for modelling the process precipitation streamflow) of CEDEX. In addition, pluviometric information is available from 30 meteorological stations located in the study basin or in its vicinity, whose data have been analysed.

Checking evaporation values

Due to the importance of the evaporation in the system, these values have been particularly important to verify. Calibrated and validated data by public administrations corresponding to four hydrological years (2013/14 to 2016/17) were available. Thus, evaporation has been calculated in the same period through the estimation equation of Penman-Monteith (Equation (1)), following the procedure detailed in Allen et al. (2006). When comparing the calculated and available values, the adjustment obtained between them is adequate (Figure 4), with a discrepancy in its average values of less than 2%.

$$ET_o = \left[\frac{\Delta}{\Delta + \gamma^*} (R_n - G) \frac{10}{L} + \frac{\gamma}{\Delta + \gamma^*} \frac{90}{T + 275} u_2 (e_s - e_a) \right] \quad (1)$$

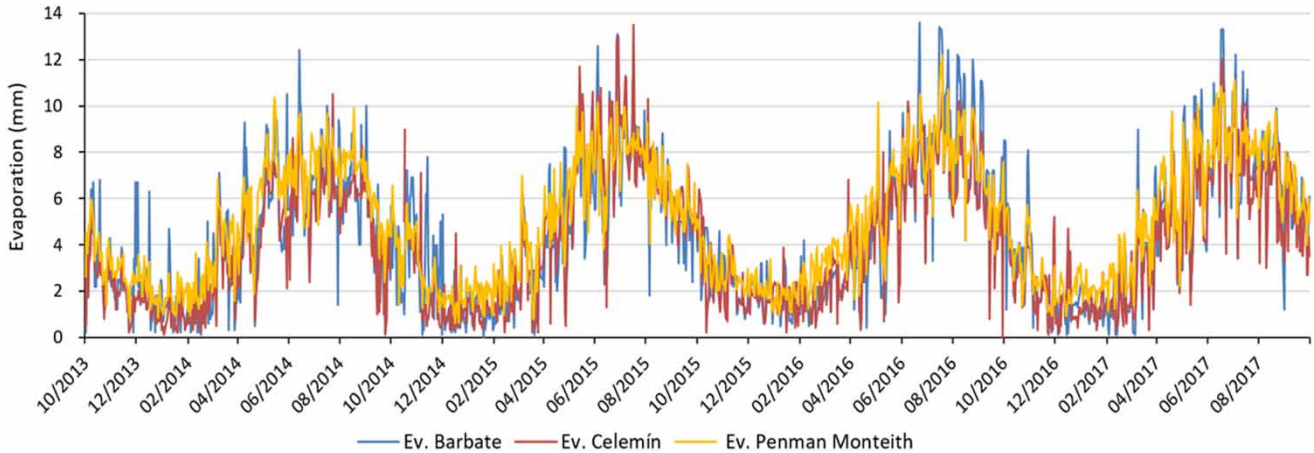


Figure 4 | Evaporation measured in Barbate and Celemín reservoirs over four years from hydrologic data. Comparison of the available values and estimated values by the Penman-Monteith method.

where ET_o is the volume of water that has undergone evapotranspiration (mm/day), γ^* and γ are psychrometric constants (mbar/C), e_s is vapour pressure with air temperature (mb), e_a is vapour pressure with dew temperature (mb), L is volumetric latent heat of vaporization (cal/gr), Δ is rate of change of saturation specific humidity with air temperature (mbar/°C), R_n is net irradiance (cal/(cm² day), T average temperature (°C) and G is ground heat flux (cal/cm²).

AQUATOOL decision support system shell

For modelling of the Barbate River basin, the DSS AQUATOOL (Andreu *et al.* 1996), and more specifically, SIMGES (Andreu *et al.* 2007), was used. AQUATOOL is a generic DSS developed at the University of Valencia, Spain. It was originally designed for the planning stage of decision-making associated with complex river basins. Its base focuses on classic system analysis methodology, but the software has been incorporating the new requirements that mark current needs through the modules. The SIMGES module solves the problem of management from a conservative flow network that is solved by optimization. For this purpose, the program uses the following objective function (Equation (2)):

$$O.F. = \text{Minimize } (T_E + T_{R1} + T_{R2} + T_{R3} + T_{R4} + T_{R5} + T_{DC} + T_{DN} + T_{RA} + T_{BA}) \quad (2)$$

where every term is an objective function corresponding to each one of the possible elements in the system – reservoir (E), river ($R1$ – $R5$), demands (DC), artificial recharge (RA), pumping (BA) and others. All these objective functions are subject to constraints related to hydraulic principles (mass conservation) and to the physical limits of transport and conduction, reservoir capacities, etc.

Since this study is an important element of the water budget, for the quantification of losses by evaporation in reservoirs, SIMGES performs the calculations on a monthly scale and applies the following formula (Equation (3)):

$$E = \frac{S_f + S_i}{2} * e * 10^{-5} \quad (3)$$

where S_f and S_i are the surface area (in ha) of the reservoir sheet corresponding to the final and initial volume, and e is the evaporation rate in mm.

Calibration and validation

Traditional methods (Oreskes *et al.* 1994) imply the use of the oldest data for calibration and the most recent for validation. In this study, the available reliable data corresponding to the last period uses a technique called ‘backwards validation’ (Paredes *et al.* 2010), in which both periods are invested. Figure 5 shows the validation periods (1999–2013) and calibration (2013–2016) for the volumes stored in the reservoirs of Barbate and Celemín.

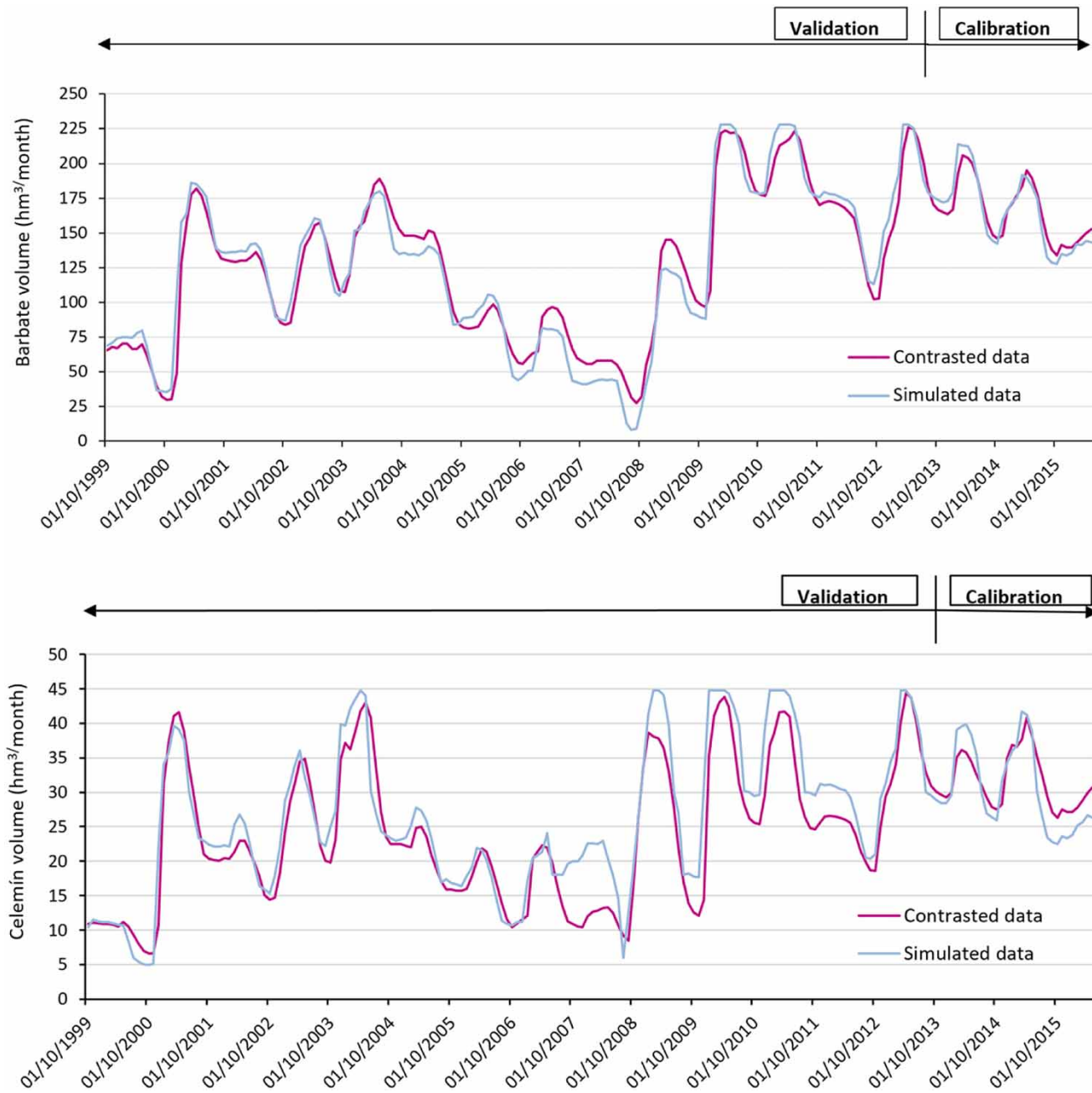


Figure 5 | Comparison of contrasted values and simulated for the calibration and validation of the model. Top: Barbate water storage. Bottom: Celemin water storage.

Analysis of scenarios

The possible management alternatives and the needs of the system were studied to determine the optimal management strategy that could be implemented without high costs and with the fewest possible environmental effects. In this

study, five possible strategies of action have been proposed: (i) conjunctive management of the reservoirs, (ii) conjunctive use of the surface-groundwater, (iii) transfer between reservoirs, (iv) artificial recharge of aquifers, and (v) combining the above strategies so they are compatible with each other. Different simulations within each strategy were

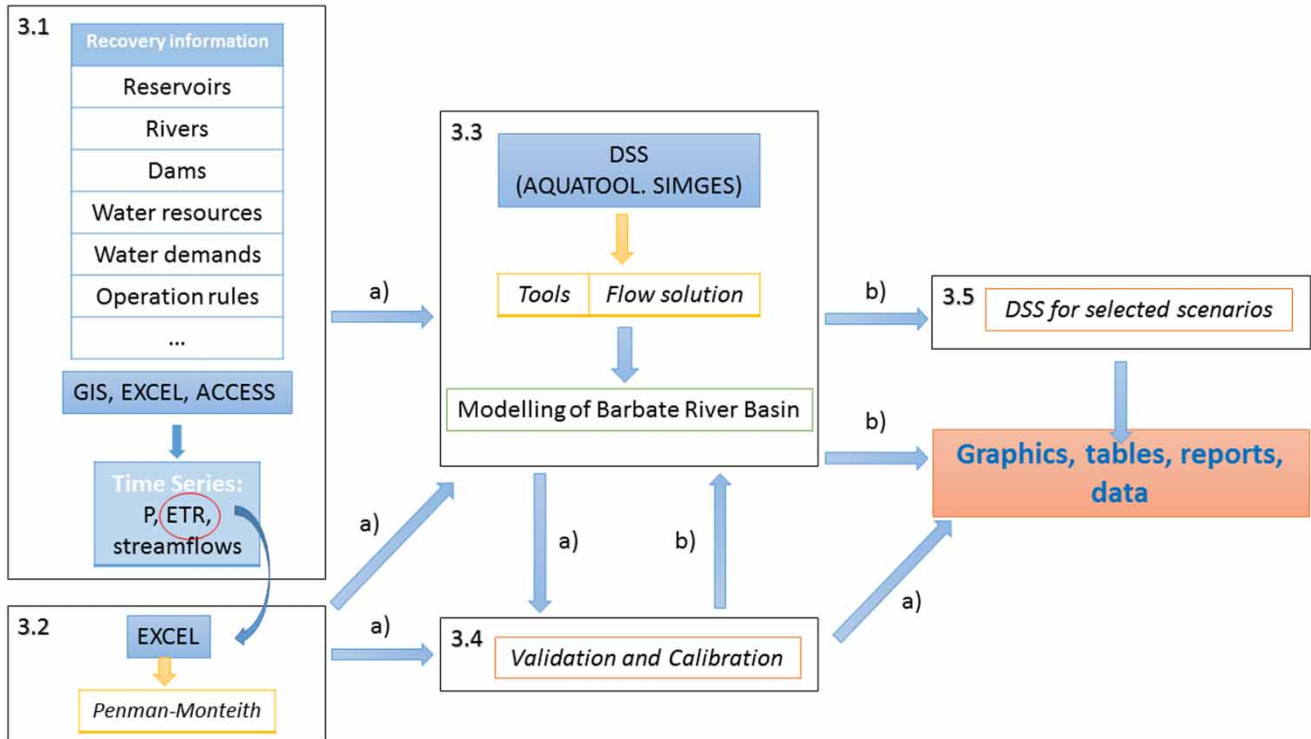


Figure 6 | Methodological scheme for the definition of management alternatives of a hydrological system.

carried out, with the management variables being modified. Finally, the advantages and disadvantages of each strategy were analysed, with optimal management being developed and compared with the current management in the basin. A scheme of the proposed methodology is shown in Figure 6.

RESULTS

By including all elements of the water system in the Barbate River basin, the simulation model was built for the current scenario with SIMGES module of AQUATOOL (Figure 7). The model reflects the complex interaction among all elements in the system.

From the current model, different simulation scenarios were raised for the optimization of water resources in the Barbate River basin. In this study, five possible action strategies were identified that are applicable to the basin, economically feasible, and with the fewest possible environmental effects. Within each strategy, different simulations

were developed (28 in total) modifying the transfer flows among the elements, system operating rules, target volumes, etc. Finally, the advantages and disadvantages of each action strategy were analysed (Table 3).

Following the analysis of the current management model, the management of the basin was determined to be very conditioned to the variations of volume in Celemín and Almodóvar reservoirs. Both reservoirs have a lower capacity of regulation (annual) and experience demands for exclusivity. For this reason, to guarantee supply to meet these demands, the management of the basin should aim at keeping the reservoirs Celemín and Almodóvar at the highest possible levels and covering most of the demands with the water stored in the Barbate reservoir (strategy 1, E1). In strategy 2 (E2, conjunctive use), the maximum pumping flows of the aquifers have been limited to a range between 0.3 and 2.0 hm³/month, depending on the current amounts pumped and the hydrogeological characteristics. In addition, different operation rules have been applied for the coordinated extraction of water from aquifers in drought times. During the execution of the Barbate dam, a

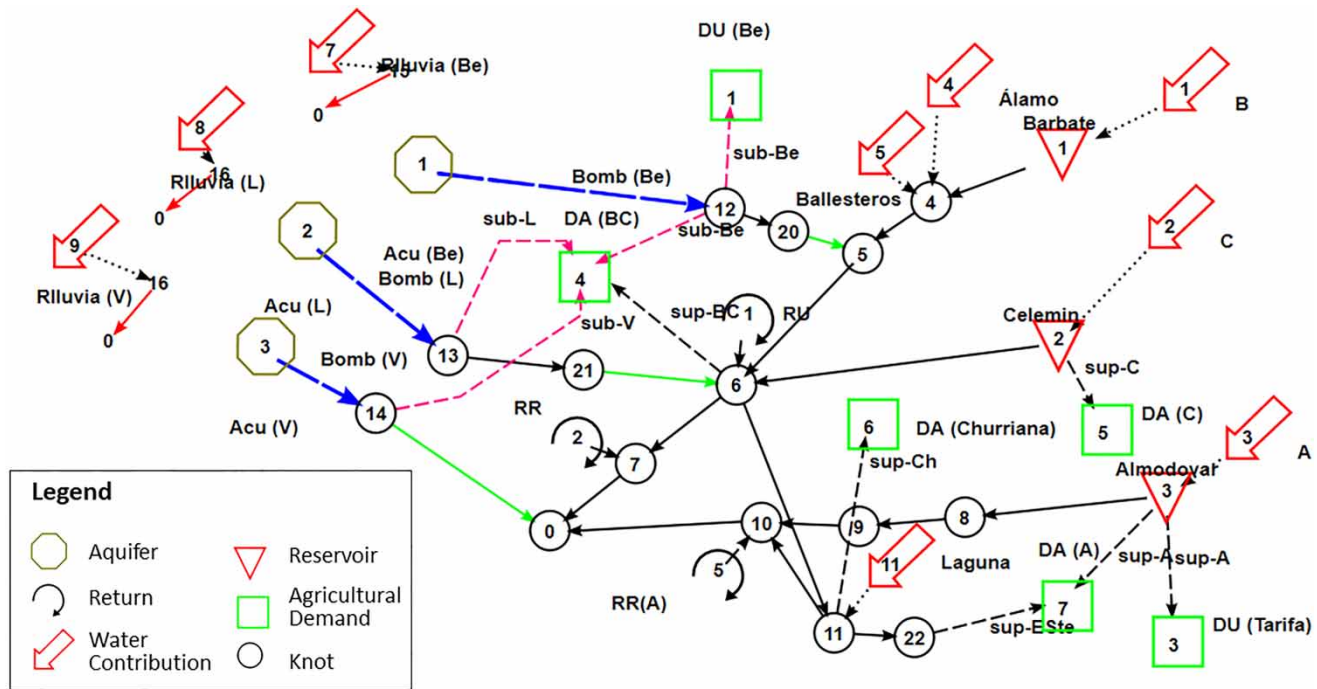


Figure 7 | Scheme of the simulation model of the Barbate River basin.

pumping station was built to transfer water from the Barbate reservoir to Celemín. This transfer allowed a maximum flow of $5.2 \text{ hm}^3/\text{month}$. These facilities, despite being in disuse and in need of rehabilitation, constitute a strategic element to consider in the management of resources of the basin (strategy 3, E3). In strategy 4 (artificial recharge of the Benalup aquifer), the recharge flows were defined according to the hydraulic calculation that would provide an optimal pre-sizing of the necessary pipes. Subsequently, for each recharge flow rate, the optimum volume for the Barbate reservoir (without affecting the guarantee demands) was established. Finally, combining the previous compatible strategies has been proposed to maximize the benefits of each one of them (strategy 5, E5).

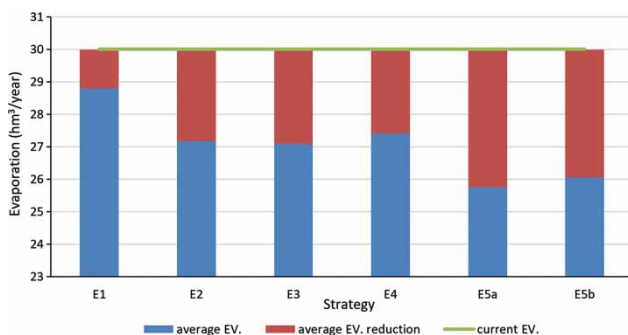
Of the three reservoirs of the basin, only Barbate has multiannual regulation capacity, since its storage volume is 2.5 times higher than the average annual inflows estimated ($86 \text{ hm}^3/\text{year}$). This gives it a strategic characteristic for storage of resources in wet years. However, this reserve is considerably diminished by the high evaporative processes produced from the water sheet, since the ratio between the evaporated volume and the volume supplied is above 0.5.

The average annual evaporation produced only in the Barbate reservoir ($30 \text{ hm}^3/\text{year}$) is much higher than the average extraction of all the aquifers in the basin ($18.5 \text{ hm}^3/\text{year}$). For this reason, the average evaporation in the period of study (1999–2016) was quantified in the 28 simulations, and the simulation that provided better results of reduction of evaporation in the water sheet of the Barbate reservoir was selected for each management strategy (Figure 8).

When the average annual evaporations in Barbate reservoir in the six options selected (Figure 9, top) were analysed, the main objective of the strategies posed was to store the resource in periods of normal or elevated precipitation in strategic reservoirs that do not suffer from a strong evaporation (aquifers and Celemín reservoir), reducing the direct evaporation from Barbate. On the other hand, in the period 2007–2011, in which the levels of the reservoirs are very depressed due to a prolonged drought, the evaporation was similar in all the strategies. However, with the proposed management options, in all cases, a reserve remained in the strategic reservoirs, deferring supply problems in the event of drought. The evaporation reductions fluctuated

Table 3 | Summary of AQUATOOL simulation scenarios

Strategy	No. simulations	Definition	Advantages	Disadvantages
E1: Conjunctive management of reservoirs	1	Using preferably the resources of the Barbate reservoir to reduce the level (and therefore the flooded area) and at the same time maintain the level of the Celemín at its highest elevation, maintaining protection against the avenues	Improvement of demands reliability. Reduction of evaporation loss. No economic and social cost (no auxiliary constructions required)	Not improving the GWB state
E2: Conjunctive use surface-groundwater	9	Use of surface water instead of groundwater to supply agricultural demand, except in drought situation	Improvement of aquifers' state. Improvement of demands reliability. Reduction of evaporation loss. Reduction of the energy cost by decrease of the pumping time and by elevation in the piezometric level (PL)	Economic cost of construction of distribution network for plots without access to surface water. Social cost of users who have their own wells and manage them in a particular way
E3: Transfer between reservoirs	5	Elevation of resources from Barbate to Celemín reservoir using a disused pumping station. Pumping flow limited by the old conduction	Improvement of demands reliability. Reduction of evaporation loss. No social cost for the alteration of the existing private facilities	Rehabilitation cost of pumping facilities. Energy cost.
E4: Artificial recharge of Benalup aquifer	11	Water transfer to the Benalup aquifer from the Barbate reservoir. Recharge of other aquifers is ruled out by its hydrogeological conditions and the need for detailed studies	Improvement of demands reliability. Reduction of evaporation loss. Improvement of the Benalup aquifer state	Construction cost of recharge installations. Energy cost. There is no integral improvement of all groundwater bodies
E5: Combination of previous strategies	2	Combining compatible strategies: Conjunctive use + transfer (E5a). Recharge + transfer (E5b)	Improvement of aquifers' state. improvement of demands reliability. Greater reduction of evaporation loss	Construction cost of distribution network. Rehabilitation cost of pumping installations. Energy cost. Social cost of users who have their own wells and manage them in a particular way

**Figure 8** | Evaporation in each management strategy and decrease of this in respect of the current management of the Barbate River basin.

according to the strategy between 0 and 10 hm³/year (Figure 9, bottom).

DISCUSSION

After analysing the advantages and disadvantages of the simulations performed and the variable evaporation in the system, the most suitable management strategy for the Barbate River basin would be to implement a conjunctive use of surface water and groundwater and simultaneously

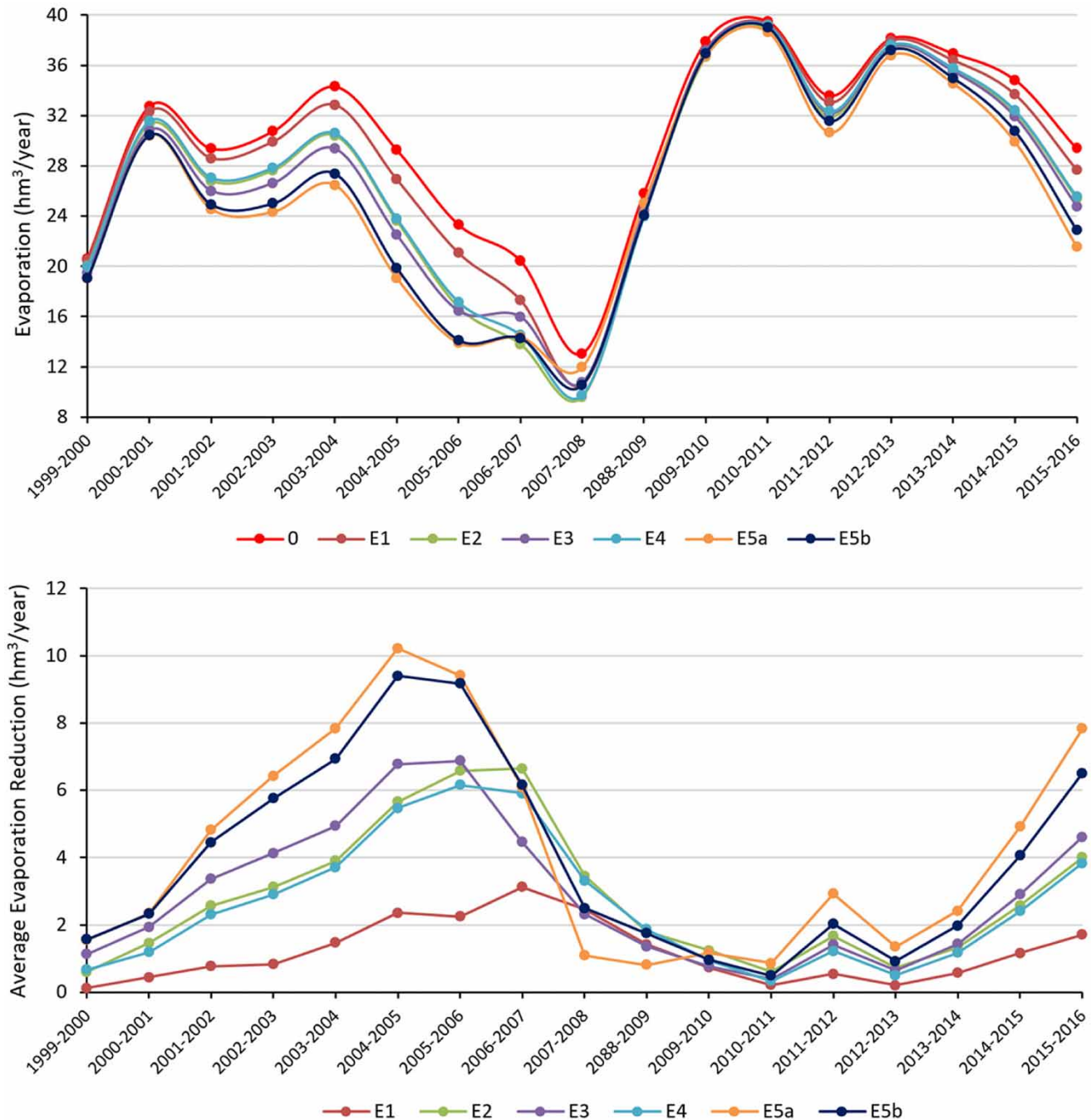


Figure 9 | Top: average annual evaporation in the current management (0) and in the proposed options (E1–E5b). Bottom: evaporation reduction with respect to the current management.

transfer water from the reservoir of Barbate to Celemín, as long as the levels of both reservoirs allow it (strategy E5a). With this combined strategy, the reliability of the supply to all demands is 100%, the qualitative and quantitative state

of the aquifers will improve, and the direct evaporation in the Barbate reservoir will be reduced.

Under the management strategy E5a (Figure 10, top), the agrarian demands could have been met with surface

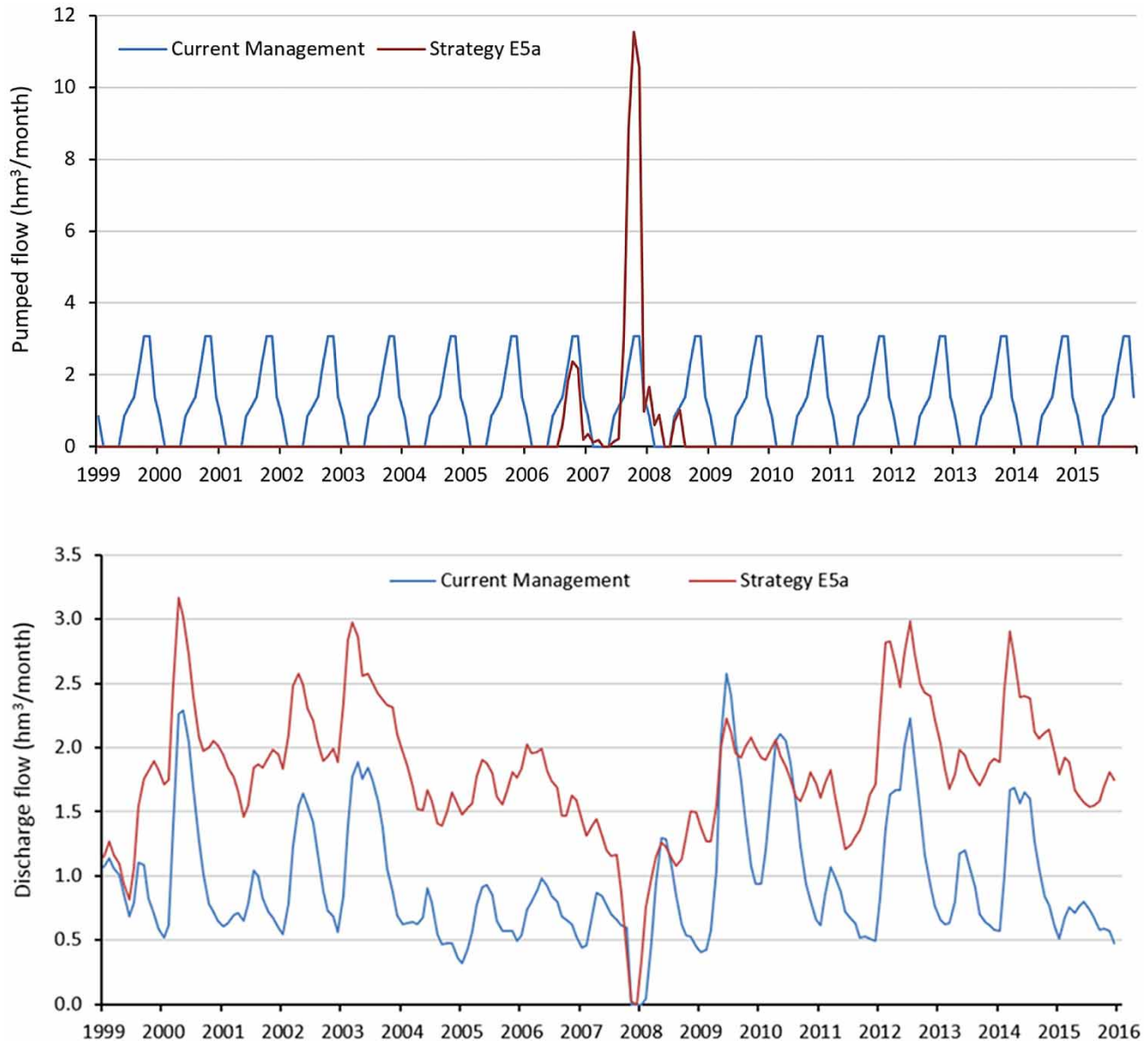


Figure 10 | Top: Pumping volume of aquifers for irrigation. Bottom: Natural discharge returning to the system as surface runoff.

water in a substantial part of the study period, except during the drought suffered between 2006 and 2009. With the current management, 238 hm^3 of water have been withdrawn from the aquifers for irrigation in 17 years. However, with the raised strategy, this pumping could have been reduced to 48 hm^3 , which is an 80% reduction. With the proposed management modifications, the living reserves of the aquifers would increase, boosting the capacity to dampen the periods of drought through

storage in humid years, while favouring the interannual regulation. In addition, this resource stored in the aquifers is exempt from the evaporation problems that would be suffered in the superficial reservoirs. Notice that with the decrease in groundwater extraction, an increase in the natural discharge of these would be experienced, especially by the elevated topographical disposition of the Benalup aquifer. These natural discharges would increase to 21.8 hm^3/year , quantified in the current exploitation of

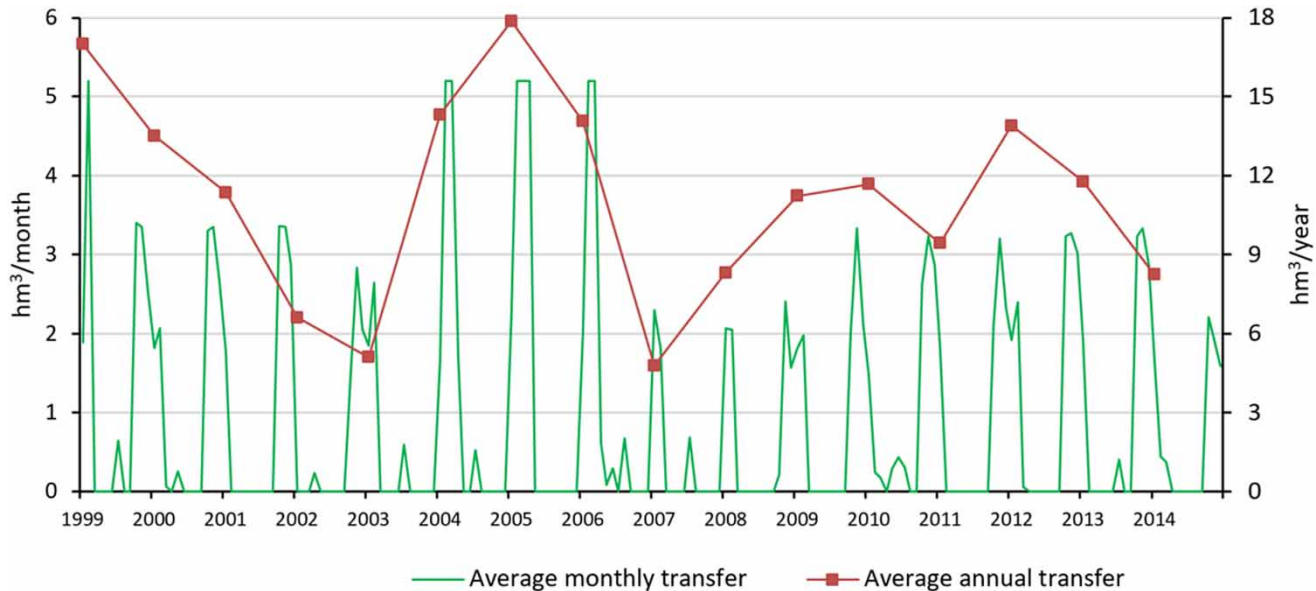


Figure 11 | Monthly and annual average flows transferred between Barbate and Celemin reservoirs in the proposed strategy (E5a).

the system at $11.5 \text{ hm}^3/\text{year}$ (Figure 10, bottom). This difference in volume returns to the system, with the water being usable for the agrarian demand of the basin. In addition, this approach suggests the riverside ecosystems will also improve, according to the line marked by the Water Framework Directive. In addition, the maximum deficit of the demands of the system was 3.4 hm^3 . This information was obtained from the agrarian demand, that depends exclusively on the Celemín reservoir during the hydrologic year 2000/2001. This deficit could have been eliminated through the proposed strategy, proving the ability of the system to delay the effects of drought for at least one year.

A strategic element in this management is also considered to make a transfer between the reservoirs of Barbate and Celemín. The average annual flow rate varies between 5 and 27 hm^3 , with monthly values between 0 and 5.2 hm^3 (Figure 11).

One of the objectives of this work has been to quantify and reduce the evaporation output suffered by the system in the main reservoirs. The reduction of evaporation that is achieved in the Barbate reservoir with the proposed strategy (E5a) is diminished by the increase of this variable in the Celemín reservoir (Figure 12). In the Almodóvar reservoir, due to its characteristics and very limited

management by the urban demand of Tarifa, the difference of evaporation between the current management and the proposal is practically nil. When the evaporation in both reservoirs is analysed as a single element during three years of the study period, the E5a strategy implies an increase in the evaporation of the system, although with values close to zero. This is shown in Figure 12 (bottom) in the negative values of the graph (grey variable). For the remaining years, water is gained, with a continuous growth of this gain when the slope is positive and with a slowdown of this variable when the slope of the graph is negative. During the 17 years analysed, the total evaporation in the reservoir of Barbate would go from 510 hm^3 in the current situation, to 438 hm^3 with the proposed strategy. However, in Celemín reservoir, the evaporation would increase from 110 to 132 hm^3 , so that the total gain of water in the system would have been almost 50 hm^3 ($2.8 \text{ hm}^3/\text{year}$) (Figure 12, bottom). However, if the water supply is analysed for short periods of time, in just five years (1999–2005), 34 hm^3 ($6.8 \text{ hm}^3/\text{year}$) would have been stored, of which 8.5 hm^3 corresponds to only the hydrologic year 2004–2005, which would have been available for subsequent drought, delaying the effects of this one. The increase in the loss of water to the atmosphere caused by the presence of the water sheet in

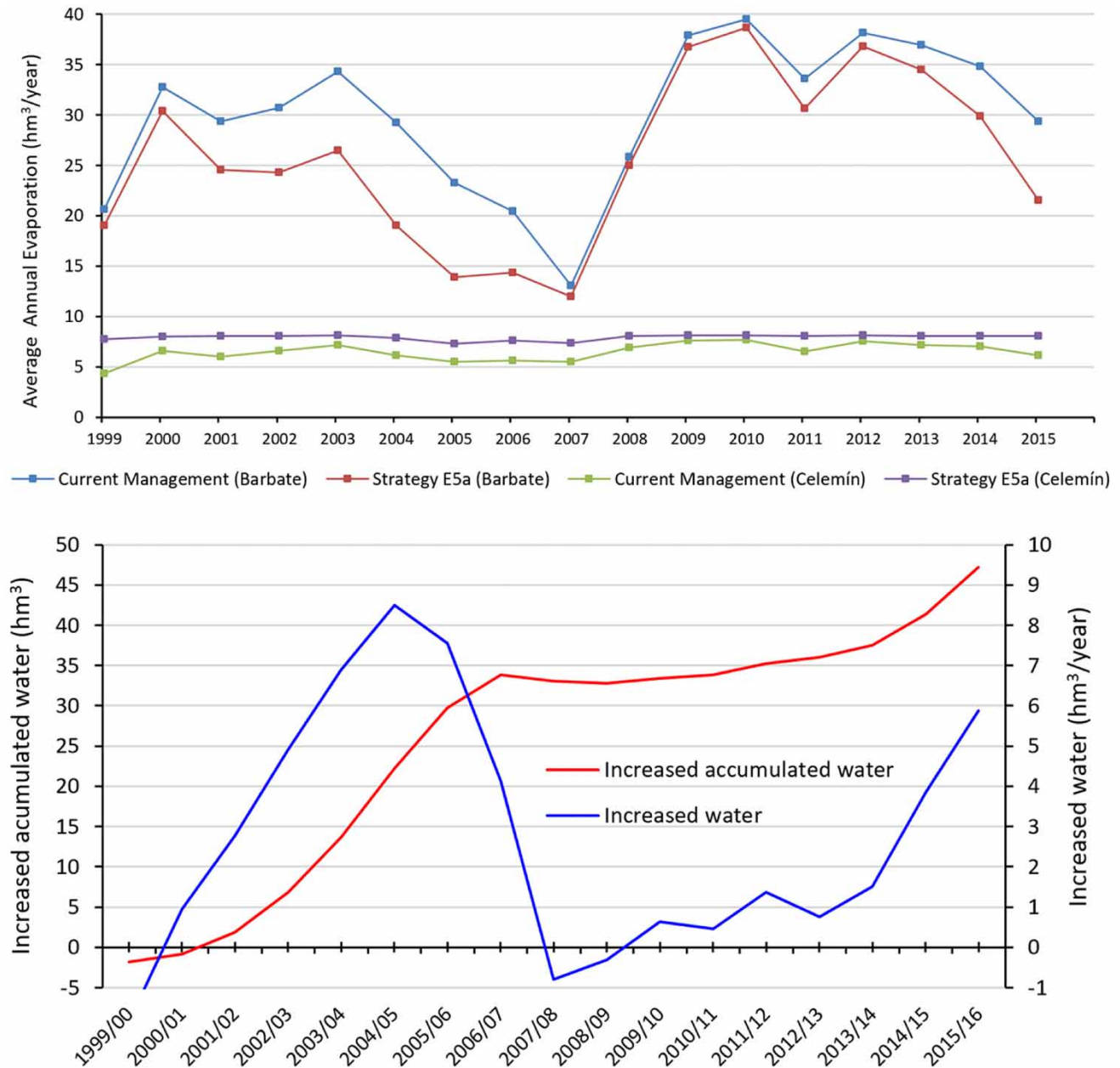


Figure 12 | Top: annual average evaporation of Barbate and Celemin reservoirs in the current and proposed management. Bottom: Average annual resource gain and accumulated by evaporation balance in Barbate and Celemin reservoirs.

a reservoir with respect to the non-flooding situation is less than the absolute value of the losses (Témez 2007). The transfer to the atmosphere is also produced from the unflooded soil so that, in the rainy periods, the actual evapotranspiration and the potential practically coincide, regardless of whether the terrain is flooded or not.

However, in arid climates, or in the climates with periods of strong drought as the one that occupies us, the water shortage in the soil can become very high, which implies that the losses from a non-flooded surface are very close to zero, while the losses from the free sheet are maximum.

Table 4 | Summary of the main variables analysed in the current management of the basin and the proposed management (E5a)

	Current management	E5a	Difference
ET average at Barbate (hm ³ /year)	30.0	25.8	4.2
Vol. average dammed at Barbate (hm ³ /year)	127.8	100.3	27.5
Sup. average of water sheet at Barbate (ha)	1,913.9	1,704.5	209.4
ET average at Celemín (hm ³ /year)	6.5	7.9	-1.4
Vol. average dammed at Celemín (hm ³ /year)	26.6	41.5	-14.9
Sup. average of water sheet at Celemín (ha)	408.2	469.8	-61.6
Surface supply for irrigation (hm ³ /year)	42.3	53.5	-11.2
Transfer from Barbate to Celemín (hm ³ /year)	0.0	12.1	-12.1
Amount pumped from aquifers (hm ³ /year)	14.0	1.9	12.1
Natural discharge (aquifers) to the system (hm ³ /year)	11.5	21.8	-10.3

Table 4 summarizes the main data and variables analysed in the current management and in the proposal.

Although the reduction in the volume evaporated from the Barbate reservoir under the proposed strategy can be considered relatively small, when implemented ahead of a scenario of climate change, with the increase in average temperature and the duration and intensity of the heat waves and therefore evaporation, the strategic approach becomes more effective. In addition, the increase in the demands would aggravate the problem of resource availability so that the quantitative and qualitative improvement of aquifers marks the basin management guidelines. The administration, according to the current regulations (BOE 2007), is obliged to propose a programme of action for the recovery of the good state of the aquifers, which must include the ordination of the extractive regime, currently controlled by the users, and the dictation of rules in the use of water to achieve a rational exploitation of the resource. Hence, the implementation of a conjunctive and rational use of the surface water and groundwater, based on scientific knowledge, is the basis of future management strategies in the Barbate basin.

CONCLUSIONS

The proposed methodology is based on the use of decision support systems (AQUATOOL-SIMGES) to allow decision-makers to detect characteristics and improve aspects of a basin from the point of view of water management. In addition, it allows appropriate management strategies to be defined with the lowest possible cost of implementation and fewer environmental effects. To evaluate the applicability of the proposed methodology, it has been implemented in the Barbate River basin (Cádiz, Spain).

Water demands satisfied with the resources of the Barbate River basin are continually threatened by limited underground resources due to the bad state of the GWB, by the singularities of the existing reservoirs (two of them with a very reduced capacity of regulation and the third one with important problems of evaporation) and because the basin is subjected to high water stress (WEI > 40%), etc. The results of this study determined that the conjunctive use of surface water and groundwater constitutes the key to basin management. It allows the live aquifer reserves to increase, boosting their capacity to cushion periods of drought through storage in wet years, promoting interannual regulation, reducing pollution by increasing dilution processes and improving riparian ecosystems by increasing natural discharges.

On the other hand, the direct evaporation from the water sheet of the reservoirs, especially in the Barbate, constitutes an important element in the management of the basin so that an integral improvement in the management of the system implies the control and reduction of this output of the water balance. The existence of a transfer, currently in disuse, between the Barbate and Celemín reservoirs, allows the incorporation of this variable into the management of the basin and contributes to the decrease of the high evaporation rate that occurs in the Barbate reservoir.

The selected management strategy (conjunctive use of surface water and groundwater plus transfer between reservoirs) shows better optimization of the resource. The key to this option is to store the resource during times of normal or elevated rainfall in the strategic reservoirs that suffer less evaporation (Celemín reservoir and aquifers) for availability during times of drought. In this sense, in just five years (1999–2005), 34 hm³ more (6.8 hm³/year) would

have been available, which could have been used in the period of subsequent drought. In addition, the supply restrictions suffered in the area could have been delayed for at least one year, which in the southern part of Spain, which has a marked cyclicality in dry and humid periods, could be very relevant. The increase in the availability of resources may seem small for the whole basin, but it should be noted that, for groundwater users, that amount represents the difference between being classified as good or poor quantitative condition.

Finally, this study aims to contribute to the objectives of the ‘Blueprint to safeguard Europe’s water resources’ (EC 2012) so that the results obtained here can be taken into account for the improvement of the knowledge of the Spanish basins, whose methodological guidelines for action are included in the ‘Hydrologic Planning Instruction’ (BOE 2008).

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