Socio-Economic Impact of Evaporation Losses from Reservoirs Under Past, Current and Future Water Availability Scenarios in the Semi-Arid Segura Basin

J. F. Maestre-Valero · D. Martínez-Granados ·
V. Martínez-Alvarez · J. Calatrava

Abstract This study assesses evaporation losses from water reservoirs in the semi-arid Segura basin (south-east Spain), one of the most water stressed European catchments. These losses are evaluated from both the hydrologic and economic perspectives under different water availability scenarios that are based on water policy trends and climate change predictions. We take a multidisciplinary approach to the analysis, combining energy balance models to assess the effect of climate change on evaporation from water bodies, Class-A pan data and pan coefficients to determine evaporation loss on a regional scale, and non-linear mathematical programming modelling to simulate the economic impact of water use and allocation in the basin. Our results indicate that water availability could be reduced by up to 40 % in the worst-case scenario, with an economic impact in the 32–36 % range, depending on the indicator in question. The total annual evaporation loss from reservoirs ranges from 6.5 % to 11.7 % of the water resources available for irrigation in the basin, where evaporation from small reservoirs is more than twice that from large dams. The economic impact of such losses increases with water scarcity, ranging from 4.3 % to 12.3 % of the value of agricultural production, 4.0 % to 12.0 % of net margin, 5.8 % to 10.7 % of the irrigated area, and 5.4 % to 13.5 % of agricultural employment. Results illustrate the importance of evaporation losses from reservoirs in this region and the marked upward trend for future scenarios. Besides, they highlight the extent of the impact of climate change on future water resources availability and use in southern Europe.

Keywords Water management · Climate change · Water economics · Value of water · Dams

1 Introduction

Population growth, economic, social and urban development and, especially, irrigation have led to large increases in water demands in Mediterranean countries. This has resulted in

J. F. Maestre-Valero (✉) · D. Martínez-Granados · V. Martínez-Alvarez · J. Calatrava
Universidad Politécnica de Cartagena. Escuela Técnica Superior de Ingeniería Agronómica, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain
e-mail: josef.maestre@upct.es

extensive water withdrawals that have come to exceed renewable water resources in some regions, putting increasing pressure on water resources (Iglesias et al. 2007). Climate change (CC) forecasts for Mediterranean countries suggest that the situation is likely to worsen in the near future (IPCC 2007). The area affected by water shortages might increase within a short time span, leading to increasing competition for available water resources (Alcamo et al. 2003; Schröter et al. 2005) and to potential conflicts between users and regional administrations (MED WS&D WG 2007; Iglesias 2009). Therefore, the development and application of scientific knowledge on sustainable water resources management is of paramount importance in Mediterranean countries (Christodoulou 2011).

Long-term water scarcity, a concept normally used to show the inability of an area's exploitable water resources to cover current and future water demands (Tsakiris and Spiliotis 2011), is especially severe in the Segura, a semi-arid basin located in south-east Spain. Although the basin usually receives external resources from central Spain through the Tajo-Segura Aqueduct (TSA), the huge expansion of the irrigated area over the last 3 decades has caused a chronic structural water deficit that positions the Segura as one of the most water stressed basins in the Mediterranean (MED WS&D WG 2007). In fact, the Spanish Government selected the Segura as the Spanish Pilot River Basin within the European Water Scarcity and Drought Expert Network. It currently suffers from water management problems, which, as a result of CC and increasing water withdrawals, will be surely common in most Mediterranean regions in the coming decades.

In arid and semi-arid regions, evaporation losses from water reservoirs can be potentially large (Gupta et al. 2002; Craig et al. 2005; Gökbulak and Özhan 2006). Martínez-Granados et al. (2011) estimated the annual evaporation loss from water reservoirs for the Segura basin at around 78 hm^3 (8.6 % of the current estimated water consumption for irrigation and 6.8 % of the current estimated total water consumption). Such a loss affects the overall water use efficiency in agriculture and counterbalances most of the efficiency gains derived from generalized improvements in irrigation water distribution and application systems.

Moreover, CC predictions project an increasing water stress for southern Europe. The Intergovernmental Panel on Climate Change expects that predicted changes in temperature and precipitation in the Mediterranean basin will lead to substantial decreases in available water resources, even by 40 % (IPCC 2008). Additionally, evaporation from open-water surfaces is projected to increase since the atmosphere's water-holding capacity increases at higher temperatures, whereas relative humidity is not projected to change markedly. As a result, water vapour deficit in the atmosphere will increase, as will the evaporation rate (Trenberth et al. 2003).

In view of the relative importance of evaporation losses from water storages and the severity of CC predictions, it is crucial to assess their magnitude and economic impact in water stressed regions, such as the semi-arid Segura basin, to optimize water surveying, planning and management.

There are very few studies dealing with the effect of CC on evaporation from water bodies. Schindler and Donahue (2006) reported in research on the Experimental Lakes Area northwest of Kenora (Canada) that, with a rise of 2 °C in average air temperature, the lake water temperature would increase by about 1.5 °C, suggesting a substantial increase in evaporation losses. Jurak (1989) suggested that evaporation from shallow water bodies would increase by 11–24 % on the 49th parallel of latitude in Europe for a warming of 2.8 °C. In agreement with this, we believe the key issue for the analysis of the effect of CC on evaporation from water bodies is an accurate computation of water temperature increases. In that sense, straightforward mechanistic models such as the one proposed by Martínez-Alvarez et al. (2007), might forecast (under future scenarios considering CC predictions) daily surface water temperature and evaporation by numerically solving the energy balance at the water body surface.

In addition, there are only a few studies assessing the impact of evaporation losses from an economic perspective (Ward 1987; Craig et al. 2005; Martínez-Granados et al. 2011). Specifically, Martínez-Granados et al. (2011) assessed the economic impact of evaporation losses from water reservoirs in the Segura basin. However, no economic assessment of evaporation losses under future water availability scenarios has been published to date. As the agricultural sector is usually the sector most affected by water shortages, any assessment of water evaporation losses should consider the economic impact on irrigation.

Among the existing alternative methodologies for the economic valuation of irrigation water, mathematical programming is the most powerful tool for valuing water resources in agricultural systems with more than one crop, as it requires fewer data than other more costly methods (Young 2005). Furthermore, agro-economic optimization models are the most used approach for the economic valuation of water use in agriculture (Amini Fasakhodi et al 2010; Carmona et al. 2011; Regulwar and Gurav 2011; Martínez-Granados et al. 2011). One of the major advantages of this type of models is that they are able to estimate the economic impact of changes on the technical-economic parameters used in the model (water availability, crop yields, prices, costs, etc.) in order to evaluate future management alternatives at different spatial levels or future scenarios of increased scarcity, such as CC predictions or socio-political debates.

This study has multiple original contributions. First, we quantify the impact of future CC predictions on evaporation from water bodies in the Segura basin. Second, we assess the increasing relevance of evaporation losses from water reservoirs under five different water availability scenarios. Third, we evaluate the social and economic impact of such water losses. Finally, we assess the economic impact of the future CC scenarios on the basin's irrigated agriculture; this is a more accurate assessment as it accounts for the increased evaporation losses.

2 The Segura Basin and Water Reservoirs

The Segura basin is one of the most water stressed regions in the Mediterranean basin. It is a predominantly agricultural region, where 9,830 km^2 (52.1 % of the basin area) is agricultural land, 6,800 km^2 is currently cultivated, and a maximum of 2,420 km^2 is irrigated land (CHS 2007). The irrigated horticultural sector plays a major role in the basin's economy in terms of production, employment and exports.

According to the Segura River Basin Authority (CHS 2007), the basin faces a structural water deficit that amounts to 370 hm^3 yr^{-1}. Available water resources are 1,592 hm^3 yr^{-1} sourced surface water (623 hm^3 yr^{-1}; 39.1 %), groundwater (200 hm^3 yr^{-1}; 12.6 %), reuse (146 hm^3 yr^{-1}; 9.2 %), desalinised (83 hm^3 yr^{-1}; 5.2 %) and external water sources from the adjacent Tajo basin (540 hm^3 yr^{-1}; 33.9 %). These available water resources are not enough to satisfy the water demand in the Segura basin, estimated at 1,962 hm^3 yr^{-1}. Water demand is to cover crop irrigation (1,662 hm^3 yr^{-1}; 84.6 %), urban use (217 hm^3 yr^{-1}; 11.1 %), industrial use (23 hm^3 yr^{-1}; 1.2 %) and environmental use (60 hm^3 yr^{-1}; 3.1 %). This structural deficit is covered by non-renewable groundwater pumping (approximately 140 hm^3 yr^{-1}) and with deficit water application to crops (approximately 230 hm^3 yr^{-1}). Considering this deficit application of irrigation water, the real irrigation demand is 1,432 hm^3 yr^{-1}. These data about water resources availability apply in theory only. They are used for planning purposes only and represent an unrealistic optimistic scenario since there has been a downward trend in renewable water resources over the last decades and the TSA has never transferred the maximum legal water allotment from the Tajo basin.

Two types of water reservoirs can be found in the Segura basin. On the one hand, there are small reservoirs that are typically used for irrigation purposes (agricultural water reservoirs, AWRs). They usually have a moderate surface area (from 0.1 to 3 ha), a shallow depth (from 5 to 10 m) and are designed to help cope with the variable water allotments and periods without supply, guaranteeing water all year round. Such small-scale reservoirs are very numerous in arid and semi-arid regions (Krol et al. 2011). According to Martínez-Alvarez et al. (2008), there are about 1.5×10^4 AWRs across the Segura basin.

On the other hand, there are Great Dams (GDs), owned and managed by the Confederación Hidrográfica del Segura (CHS), which are instream large-sized reservoirs with a surface area ranging from 0.2 to 15 km^2 and a storage capacity from 0.07 to 250 hm^3. To simplify the analysis, in this study we consider the largest 14 of the 33 extant GDs in the Segura basin (totalling 93 % of the area covered by GDs and 96 % of the basin's total storage capacity).

Conversely to great dams, small reservoirs depict an insurance role against irrigation water supply uncertainty by maintaining their evaporative surface regardless the water scarcity condition. In a case study with unfavourable CC predictions (reduction of 10 % in annual precipitation and increase of 15 % in reference evaporation by 2100), Krol et al. (2011) showed that CC impacts on water availability from small reservoirs might exceed impacts from great dams. Accordingly, the effect of evaporation losses on water availability in future scenarios should be analysed separately for small reservoirs and great dams.

For further information on the physical environment, the agricultural sector, the water budget or the water reservoirs in the Segura basin, see Martínez-Granados et al. (2011) and Calatrava and Martínez-Granados (2012).

3 Climate Change Predictions for the Segura Basin

According to IPCC (2007), a very broad spectrum of future changes in regional temperature and precipitation are possible. However, the average modelling results coming from the most likely predictions provide good reference values for defining future possible regional CC scenarios (Alcamo et al. 2007).

Many studies indicate that the Mediterranean basin will be the most severely affected region in Europe (Giorgi and Lionello 2008). The already hot and semi-arid climate of Mediterranean areas is expected to become still warmer and drier, threatening its waterways, aquifers, hydropower, agricultural production and timber harvests (Moreno et al. 2005; IPCC 2007, 2008).

Future water availability forecasts suggest that water availability will decrease by up to 16 % in the 2030 scenario (MIMAM 2000) and by up to 28 % in the 2060 scenario (Moreno et al. 2005) compared with the current situation in the basin. These projections match IPCC predictions.

Dealing with temperature projections, the mean air temperature is expected to increase by 1 °C and 2.5 °C in the 2030 and 2060 scenarios, respectively (MIMAM 2000; Moreno et al. 2005). These temperature increases were expected to raise the evaporation rate over open water by 3.1 % and 7.7 %, in the Segura basin respectively.

4 Methodology

The proposed methodological approach focuses on the comparative analysis of scenarios. Scenarios are hypothetical sequences of events used to explore the unpredictable and uncontrollable features of change. Scenarios can form a picture of the future, which should

not, however, be construed as a prediction or forecast (Menzel and Matovelle 2010). Five scenarios of increased scarcity in water availability were considered (Section 4.1).

We have used a multidisciplinary approach to study the hydrological and economic impacts of evaporation losses on the Segura basin under the defined scenarios. This approach combines (i) the application of energy balance models for assessing the effect of CC on evaporation from water bodies, (ii) the use of Class-A pan data and regionally calibrated pan coefficients for determining the evaporation loss at a regional scale and (iii) non-linear mathematical programming modelling to evaluate the economic impact of such losses on irrigated agriculture.

In order to focus the economic analysis on the impact of evaporation losses and to distinguish between impacts from AWRs and from GDs, we have considered three different "evaporation situations" for each water availability scenario:

A. Situation without evaporation water losses.
B. Situation with evaporation losses from GDs. This is the same water availability situation considered by CHS, the regional water agency responsible for water planning and management in the Segura basin.
C. Situation with losses from both GDs and AWRs.

Situation A is not realistic but has been considered as a benchmark for comparison with evaporation situations B and C. The difference between the economic values associated with situations A and B is a measure of the impact of water evaporation losses from GDs. The difference between situations B and C is a measure of the economic impact of water evaporation losses from AWRs. Finally, the difference between situations A and C is a measure of the impact of water evaporation losses from both GDs and AWRs.

4.1 Water Availability Scenarios

Water availability scenarios (SC) are defined as follows (Table 1):

1. Recent past scenario (SC1). Scenario 1 represents the theoretical baseline scenario and is based on official irrigation water resources data from the Spanish National Hydrological Plan (MIMAM 2001). This National Plan is based on the average annual renewable water resources inflows for 1940–1996 and assumes that the Tajo-Segura Aqueduct always transfers its maximum legal water allotment for irrigation (399.8 $hm^3 yr^{-1}$).
2. Scenario 2 (SC2) called "current situation" assumes that the TSA only serves half of its maximum transferable water allotment, and that the basin surface and groundwater resources are 20 % less than in the baseline scenario. These reductions are equivalent to the average annual renewable water resources inflows for the 1980–2005 period (a 20 % decrease over 1940–1996) and the average amount of water effectively transferred for irrigation by the TSA between 1979 and 2009. This current scenario is equivalent to a 27.5 % reduction in water availability in the basin with respect to the baseline scenario (Table 1).
3. Scenario 3 (SC3) is equivalent to SC2, except that it considers that no irrigation water is transferred to the Segura basin through the TSA. Due to both increasing water scarcity and growing demands in the Tajo basin, legislative processes are now under discussion that could result in the cancellation of the TSA water transfer, at least for non-domestic purposes, making this a feasible scenario in the near future. This scenario is equivalent to a 41.2 % reduction in water availability with respect to the baseline scenario (Table1).
4. Scenario 4 (SC4) is the projected effect of CC on available water resources and the evaporation rate from open water for 2030, plus TSA water transfer cancellation.

Table 1 Available water resources by source and percentage water availability in proposed scenarios with respect to the baseline scenario in the Segura basin. TSA: Tajo Segura Aqueduct

Water resources	Water availability scenario									
	Scenario 1 Baseline scenario		Scenario 2 Current situation		Scenario 3 Current situation without TSA		Scenario 4 2030 scenario without TSA		Scenario 5 2060 scenario without TSA	
	Hm^3	%	Hm^3	%	Hm^3	%	Hm^3	%	Hm^3	%
Surface resources	538.6	100	430.9	80	430.9	80	361.9	67,2	310.2	57.6
Tajo-Segura Aqueduct	399.8	100	199.9	50	0	0	0	0	0	0
Groundwater	411.8	100	324.4	80	324.4	80	276.8	67,2	237.2	57.6
Desalinized water	53.6	100	53.6	100	53.6	100	53.6	100	53.6	100
Treated wastewater	28.6	100	28.6	100	28.6	100	28.6	100	28.6	100
Total resources	1,432.4	100	1,042.4	72.8	842.5	58.8	720.9	50.3	626.6	44.0

According to MIMAM (2000), the average decrease in water resources for the Segura basin estimated for 2030 is 16 % compared to the current scenario, equivalent to a 32.8 % reduction in the basin's own surface and groundwater resources compared with the baseline scenario. This scenario amounts to a total decrease of 49.7 % in Segura basin resources for agriculture with respect to the baseline scenario (Table1). The evaporation rate is expected to rise by 3.1 % in this scenario, as justified later.

5. Scenario 5 (SC5) is similar to SC4 above, except that it considers the effect of CC for the 2060 horizon. The projected decrease of water resources in the Segura basin for this time horizon is 28 % against the current situation (Moreno et al. 2005), equivalent to a 42.4 % reduction in the basin's own resources with respect to the baseline scenario. Adding the effect of TSA cancellation, the decrease in total Segura basin resources with respect to the baseline scenario is 56.0 % (Table 1). Additionally, the evaporation rate is expected to rise by 7.7 % in this scenario.

In order to simplify the analysis, no variations have been considered in desalinized water resources or water demand for irrigation, although they could increase in the medium to long term.

4.2 Effect of Climate Change on Evaporation from Water Bodies

We applied a modelling approach based on the mathematical formulation of the water body energy balance (Martínez-Alvarez et al. 2007) in order to determine the effect of the increasing air temperature (T_a) on both the water surface temperature (T_s) and the evaporation rate (E) for the 2030 and 2060 scenarios. The model runs on daily basis, and is fed by daily meteorological data (air temperature, relative humidity, wind speed and solar global radiation) and the water body geometry (surface area, S, and depth, D). Martínez-Alvarez et al. (2008) reported that this modelling approach could be applied to accurately derive E for shallow water bodies in places where standard meteorological data are available.

The effect of CC on E was addressed by comparing simulations for situations with and without T_a change. We conducted the analysis at three locations fairly representative of the Segura basin, namely San Cayetano (coastal plain), Murcia (Segura River Valley) and

Jumilla (north of the basin), for the 2000–2004 period and for different combinations of S and D. Daily meteorological data at those stations were obtained from the *Servicio de Información Agraria de Murcia* website (http://siam.imida.es). The model was fed with real meteorological data, and data with 1 °C and 2.5 °C increases in daily T_a were simulated in order to determine the increases in T_s and E for the 2030 and 2060 scenarios, respectively (see Section 2).

A total of 270 simulations were performed over the 5-year period for the three locations, three temperature scenarios, and several geometrical configurations representative of the AWRs commonly encountered in the Segura basin: two depths ($D=5$ and 10 m) and three surface areas ($S=10^3$, 10^4 and $10^5\,\mathrm{m}^2$). The increase in E was quite similar under all the studied combinations and then its average values were considered as the expected increases in E corresponding to the 2030 and 2060 scenarios. In absence of a better estimation, these values were also applied for GDs.

4.3 Calculating Evaporation Losses

Regional evaporation losses from both AWRs and GDs were calculated using Class-A pan evaporation data and regionally calibrated pan coefficients (Martínez-Alvarez et al. 2008; Lowe et al. 2009). Evaporation from AWRs was calculated for the 2000–2006 period using the AWRs database and the methodology proposed by Martínez-Alvarez et al. (2008). Evaporation from GDs was determined following the methodology proposed by Martínez-Granados et al. (2011).

For future scenarios, the expected rise in E for the 2030 and 2060 horizons was applied. The AWR total evaporative area was the same, since AWRs will continue to serve as emergency reserve under heavier water stressed conditions. There was only one exception: AWRs placed in areas supplied exclusively with resources from the TSA were considered empty in the scenarios with water transfer cancellation. Regarding GDs, their evaporative area was decreased for each scenario taking into account the decrease in total water resources with respect to the baseline scenario and following the bathymetric curve for each GD. For further information about the evaporation losses calculation, see Martínez-Granados et al. (2011).

4.4 Obtaining the Economic Value of Water Use

We evaluated the economic impact of evaporation losses under each water availability scenario using a non-linear mathematical programming model that simulates the economic use of water in the irrigated agriculture of the Segura basin. For detailed descriptions of the model used, including its mathematical structure, its technical and economic coefficients and its calibration process, see Martínez-Granados et al. (2011) and Calatrava and Martínez-Granados (2012). We have expanded that model to include the labour requirements of each crop in order to also compute results in terms of agricultural employment.

In this study, we used the above model to simulate the economic impact of the reduction in the volume of available water caused by evaporation losses in each water demand unit of the basin. This way, we were able to estimate the economic value of such losses in each proposed water availability scenario. The economic effect of evaporation losses from reservoirs was calculated by comparing simulations for situations with and without evaporation losses, making a distinction between impacts from AWRs and from GDs (situations A, B and C). The model was also used to estimate the economic impact of the reduced water availability induced by increased water scarcity, a feature of the considered basin scenarios.

4.5 Study Areas and Results Aggregation

For water planning and management purposes, the Segura basin is divided into 63 agricultural water demand units that are characterized by their location and the water resources they use (MIMAM 2001). Evaporation losses were estimated at the water demand unit level, as was the economic valuation of water. The results were then aggregated and presented for the entire Segura basin.

4.6 Some Considerations About the Proposed Methodology and Scenarios

Despite of its numerous advantages, the proposed methodological approach has some limitations. The approach is limited by the weaknesses inherent to the methodologies used for estimating evaporation losses and valuing irrigation water, as well as the uncertainty of the CC predictions. However, these limitations are outweighed by the sound accuracy level for an assessment on such a large scale (basin level) and by the use of official meteorological, hydrologic and economic data.

Other limitations derive from the difficulty of considering some of the technical and economic coefficients used in our economic modelling for future 2060 scenarios. We have used partial equilibrium modelling, where crop prices and yields are evaluated at their historical average and production costs are evaluated at their present values. Similarly, we have considered neither changes in crop water requirements nor potential adaptation strategies for farmers. In fact, only changes in crop allocation and land abandonment have been considered as a response to changes in water availability. However, we can guess how some of these factors might evolve in qualitative terms.

For example, despite the increasing liberalization of world markets, the area's intensive export-driven horticulture is likely to see price increases as a result of reduced irrigated area, thus partly limiting the extent of the economic impact of increased scarcity. On the contrary, a quite likely increase in crop water requirements or in production costs would increase the economic impact of future scarcity scenarios. Note also that some adaptation strategies are more limited than in other areas as, for example, the potential for new water supply sources is quite reduced or because modern irrigation technologies and deficit irrigation practices are widespread in the basin. This strongly restricts the potential for further water saving in response to reduced water availability. However, there is a greater potential for technical solutions for reducing evaporation losses (see the Section 6).

5 Results

5.1 Effect of Climate Change on Evaporation from Water Bodies

The almost three hundred simulations resulted in expected average water surface temperature (T_s) rises of 0.71±0.10 °C and 1.88±0.12 °C for the 2030 and 2060 CC scenarios, respectively. These values are in agreement with figures reported by Schindler and Donahue (2006) in Canada for similar expected air temperature increases. There was a very slight variability in the mean annual T_s for the studied years and different combinations of S and D, where location in the Segura basin was responsible for most of the standard deviation.

Table 2 shows the effect of CC on evaporation (E) from water bodies for the 2030 and 2060 CC scenarios, with respect to the average values for the 2000–2004 period. The table separates the results by locations and by S values. It only includes the average values for

Table 2 Average value and standard deviation for the absolute and relative increase in annual evaporation from water bodies for the 2030 and 2060 scenarios at three locations in the Segura basin and for surface areas of 10^3, 10^4 and 10^5 m^2

Meteoro-logical station	Reservoir surface area (m^2)	2000–2004	2030 scenario			2060 scenario		
		E	E	ΔE		E	ΔE	
		mm	mm	mm	%	mm	mm	%
San Cayetano	10^3	1,788±55	1,841±58	+53±3	+2.99±0.04	1,925±60	+136±3	+7.62±0.04
	10^4	1,694±54	1,745±57	+52±2	+3.07±0.05	1,825±60	+131±2	+7.76±0.05
	10^5	1,615±54	1,665±57	+50±2	+3.11±0.05	1,742±61	+126±2	+7.83±0.05
Murcia	10^3	1,576±57	1,624±59	+48±2	+3.04±0.05	1,698±62	+122±3	+7.74±0.05
	10^4	1,481±56	1,527±59	+46±2	+3.10±0.05	1,597±60	+116±3	+7.81±0.05
	10^5	1,405±55	1,449±57	+44±2	+3.13±0.05	1,515±57	+111±3	+7.82±0.05
Jumilla	10^3	1,598±80	1,648±83	+50±2	+3.13±0.05	1,721±86	+123±3	+7.66±0.04
	10^4	1,503±78	1,550±81	+48±2	+3.18±0.05	1,619±84	+116±3	+7.72±0.05
	10^5	1,426±77	1,471±81	+46±2	+3.22±0.05	1,536±83	+110±3	+7.76±0.05
Average values =				+49±3	+3.11±0.07		+121±8	+7.74±0.07

water depths of 5 and 10 m since the effect of this variable on annual evaporation was practically negligible. According to Martínez-Alvarez et al. (2007), there were significant differences in the annual E due to inter-annual climate variations, the station location and the surface area of the reservoirs. Additionally, these differences between the three temperature scenarios were evident. However, the increase in annual E for each temperature scenario was quite similar for all studied combinations, resulting in low and uniform values of standard deviation. Therefore, we applied rises in annual E for the 2030 and 2060 scenarios equivalent to the average E value for the studied combinations (+3.1 % and +7.7 % respectively). As mentioned above, these values were also applied to GDs.

5.2 Evaporation Assessment

Table 3 shows the water availability for irrigation and evaporation losses from reservoirs in the Segura basin under the three water evaporation situations (A, B and C) for each scenario (SC1 to SC5). Situation A adds evaporation losses in GDs to the gross water availability in each scenario (situation B), whereas situation C deducts evaporation losses in AWRs from situation B. Reductions in the water availability under each scenario generally resulted in reductions of the free water surface subject to evaporation, hence reducing water losses. In relative terms, however, notable increases in evaporation losses were observed.

Evaporation from AWRs was the same in the first two scenarios (Table 3). In spite of the TSA supplying on average only half of its water allotment in SC2, there was no decrease in the volume of stored water in AWRs to guarantee their insurance role. Hence, we considered the same volume of water as in SC1 in the water loss calculation. However, the percentage of evaporation losses with respect to the water availability increased in the SC2 due to the reduction of water availability in the basin.

Evaporation from AWRs was calculated to decrease by approximately 20 % from SC1 and SC2 to SC3, SC4 and SC5 (Table 3), these reductions being mainly attributed to the suppression of the TSA in the last three scenarios. The TSA cancellation scenario also produced a decrease in the percentage evaporation losses from AWRs from SC2 to SC3 as a consequence of the removal of water losses from AWRs located at sites irrigated from this water source only.

In general, the trend in the percentage evaporation losses from AWRs with respect to the total water availability in each scenario was upward and ranges from 4.6 % to 8.3 %.

On the other hand, the evaporative area of GDs also decreased for future scenarios as a consequence of the decrease in water resources, resulting in decreasing annual evaporation

Table 3 Water availability and evaporation losses for the proposed water availability scenarios (SC1 to SC5) and evaporation situations (A, B and C) in the Segura basin

Water availability scenario	Water availability (hm³)			Evaporation losses (hm³)		
	A; No evaporation losses	B; Minus losses in GDs	C; Minus losses in AWRs	Total losses (A–C)	Losses in GDs (A–B)	Losses in AWRs (B–C)
SC1	1,460.16	1,432.40	1,365.46	94.70	27.76	66.94
SC2	1,066.09	1,042.42	975.48	90.61	23.67	66.94
SC3	866.19	842.52	790.48	75.71	23.67	52.04
SC4	743.65	720.87	668.68	74.97	22.78	52.19
SC5	651.54	629.63	575.25	76.29	21.91	54.38

of water from GDs ranging from 27.76 $hm^3 yr^{-1}$ in SC1 to 21.91 $hm^3 yr^{-1}$ in SC5. Particularly for SC2 and SC3, evaporation from GDs was unchanged since the suppression of the water transferred from the Tajo basin in SC3 did not affect the evaporation from GDs, as they are not supplied with water from the channel. As for AWRs, however, the percentage evaporation losses from GDs with respect to the water availability increased from SC1 to SC5.

On average for all scenarios, water evaporation from GDs is 41 % of total evaporation. Under the current scenario, evaporation from AWRs is almost three times losses from large reservoirs, and its relative weight will increase as water resources will decrease in future scenarios. This is due to the insurance role of AWRs against irrigation water supply uncertainty, a role that will be even more important in future scenarios and is likely to mean that they will maintain most of their evaporative surface, resulting in an increasing weight of evaporation from AWRs (Krol et al. 2011).

In short, considering the worst-case scenario (2060 horizon), water availability in the basin might be reduced by up to 40 % with respect to the current water availability scenario (SC2) and the percentage of total water losses from GDs and AWRs could reach 11.7 % of the basin's water availability.

5.3 Economic Value of Evaporation Losses Under the Different Scenarios

In general for all the scenarios, water loss from evaporation led to a reduction in the (i) market value of agricultural production in the basin, (ii) farm net margin, (iii) cultivated area and (iv) agricultural employment. The magnitude of such reductions increased from SC1 to SC5 since it is strongly dependent on water availability, as shown in Table 4.

The resulting reduction in water availability for the scenarios had important economic impacts on the basin's irrigation (Table 4). Let us compare evaporation situation C in each of the five water availability scenarios. We can observe that decreasing water availability results in progressive reductions of all the economic indicators considered. For example, if we compare the worst predicted scenario (SC5) with the current situation (SC2), the market value of agricultural production is reduced by 706 10^6 € yr^{-1} (35.3 %), the farmers' net margin by 706 10^6 € yr^{-1} (32.6 %), the irrigated area by 63,790 ha (39.4 %) and agricultural employment by 22,542 annual equivalent labour units each year (38.5 %).

The percentage reduction in the market value of agricultural production in the basin due to evaporation losses increased from 3.6 % in SC1 to 9.2 % in SC5 and from 0.7 % to 3.1 % in AWRs and GDs, respectively. The ratio between the two suggests that losses from AWRs are relatively much greater than losses from GDs. On average for all water availability scenarios, the global reduction of the market value of agricultural production due to evaporation losses is 152 10^6 € yr^{-1}, where AWRs account on average for 115 10^6 € yr^{-1}. Results in terms of foregone farm net margin paint a rather similar picture to outcomes for the market value of foregone agricultural production for all the scenarios. This is because the ratio between these two variables is fairly stable in the Segura basin at around 40 %.

As a result of decreased water availability in the proposed scenarios, the cultivated area showed a quasi-linear decline of up to 123,941 ha (47 % reduction) between SC1 and SC5 (Table 4). The effect of evaporation losses on the cultivated area also increases in line with water scarcity. On average for all water availability scenarios, the water losses result in about 12,446 ha not being cultivated in the basin, where 9,036 ha (approximately 72.5 %) are attributed to evaporation losses from AWRs.

The decrease in water availability in the basin from SC1 to SC5 led to a reduction of 38,667 annual equivalent labour units (52 % reduction). The percentage reduction due to

Table 4 Economic impact of water losses by evaporation from AWRs, GDs and totals for the proposed water availability scenarios in the Segura basin

Water availability scenario	Evaporation situations	Value of production (million € per year)	Net margin (million € per year)	Cultivated area (ha)	Agricultural labour (annual equivalent labour units)
SC1	A. Reference (no evaporation)	2,589	1,080	233,865	80,292
	B. Minus losses in GDs	2,570	1,074	230,208	79,458
	C. Minus losses in AWRs	2,477	1,037	220,193	75,958
SC2	A. Reference (no evaporation)	2,136	914	175,318	63,250
	B. Minus losses in GDs	2,112	905	172,061	62,333
	C. Minus losses in AWRs	2,002	865	161,906	58,542
SC3	A. Reference (no evaporation)	1,768	776	143,307	51,792
	B. Minus losses in GDs	1,722	754	139,908	50,375
	C. Minus losses in AWRs	1,610	707	131,383	46,625
SC4	A. Reference (no evaporation)	1,613	716	124,216	46,167
	B. Minus losses in GDs	1,567	695	120,755	44,792
	C. Minus losses in AWRs	1,441	642	112,799	40,833
SC5	A. Reference (no evaporation)	1,479	663	109,924	41,625
	B. Minus losses in GDs	1,432	642	106,647	40,167
	C. Minus losses in AWRs	1,296	583	98,116	36,000

evaporation losses increased from 5.4 % to 13.5 % from SC1 to SC5. On average, the global water losses associated with all five scenarios resulted in an annual reduction of 5,033 annual equivalent labour units, where on average 3,833 (between 75 % and 80 %) are attributed to AWRs (Table 4).

In short, considering the 2060 horizon (SC5), the worst-case scenario, the effect of evaporation losses from reservoirs amounts to a 12.4 % reduction in the value of foregone agricultural production, 12.1 % in foregone farm net margin, 10.7 % in the cultivated area and 13.5 % in the basin's agricultural employment.

Figure 1 shows the value of average production per unit of water that is lost as evaporation from AWRs and GDs for the studied water availability scenarios. Apart from being greater in both absolute and relative terms, water evaporated from AWRs is also more valuable than that lost from GDs in all scenarios (Fig. 1). For example, water evaporated from GDs in the future CC projections (SC4 and CS5) caused an average loss of 2.019 €/m^3 and 2.145 €/m^3 respectively, whereas water evaporated from AWRs caused a loss of 2.414 €/m^3 and 2.501 €/m^3 respectively. This happened because AWRs are mostly located in the most profitable areas and water losses from GDs happen before water is transported to the irrigated areas and distributed to the farms. As the marginal value of water decreases with water availability, the "per m^3" economic impact of the first reduction in water availability (evaporation losses from GDs) is always less than the "per m^3" impact of another reduction later on (evaporation losses from AWRs).
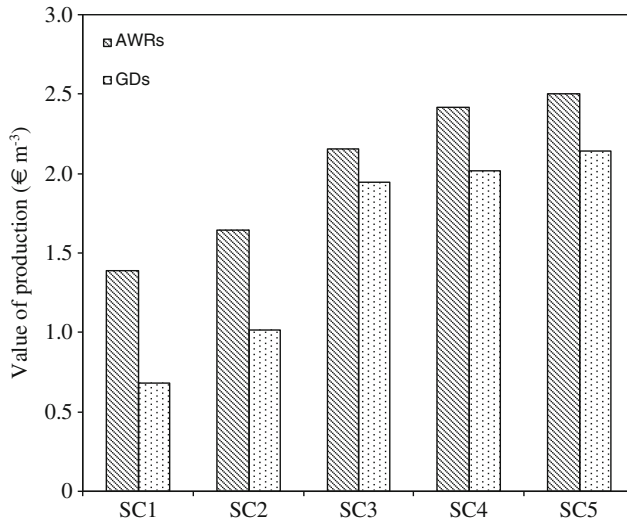
Fig. 1 Value of average production per unit of water evaporation loss from AWRs and GDs for the studied water availability scenarios

6 Conclusions

The present study provides a useful analysis that illustrates both the important role played by evaporation losses from reservoirs from the hydrological and economic perspective in the semi-arid Segura basin today and their clear and marked upward trend for future scenarios considering CC predictions and socio-political issues.

From a hydrological perspective, reductions in water availability in possible future scenarios leads to a decrease in the total amount of evaporation losses but also to a significant increase in the relative importance of water losses, reaching 11.7 % of available water resources for irrigation in the basin for the worst-case scenario (SC5). For all scenarios, evaporation from AWRs more than doubles respective losses from GDs, and its relative weight increases as water resources decrease in future scenarios.

From an economic perspective, the impact of evaporation losses is very significant, especially in more unfavourable water availability scenarios, with sizeable reductions in the (i) market value of agricultural production, (ii) farm net margin, (iii) cultivated area and (iv) agricultural employment.

These major hydrologic and economic impacts highlight the need to take into account evaporation losses for water management and planning in the Segura basin as much in the current situation as in the future projections. Besides, since evaporation losses from small reservoirs are not considered by water agencies, nor incorporated in their water budgets, the methodologies for assessing management alternatives to improve the technical and economic efficiency of water use at different levels (basin, irrigated districts and farms) would benefit by considering such evaporation losses.

In this sense, an accurate water management and planning for long-term scenarios should be based on a flexible, transparent and comprehensive multi-criteria framework (Getirana et al. 2008; Wang et al. 2008; Opricovic 2009; Tsakiris and Spiliotis 2011) and thus should include the impact of evaporation losses from reservoirs, especially for arid and semi-arid water stressed regions.

The results in this study emphasize the need for technical alternatives aimed at reducing evaporation from reservoirs in water stressed regions such as the Segura basin. Despite the wide range of techniques proposed for this purpose (Brown 1988; Craig et al. 2005), the use of suspended shade cloth covers (Martínez-Alvarez et al. 2010) and floating covers (Segal and Burstein 2010) looks to be feasible and efficient for small regular reservoirs like AWRs, whilst the use of monolayers spontaneously self-spread over the water surface, appears to be better suited for medium-sized and great reservoirs (Barnes 2008).

Additionally, the progressive water availability reduction under future scenarios is expected to increase the competition for water resources, raising the economic value of evaporated water. This should affect the profitability of this kind of measures for reducing evaporation.

However, the most common and planned strategies for adapting to increases in water stress are still supply-side measures such as impounding rivers to form instream reservoirs to increase water storage (Santos et al. 2002; Moreno et al. 2005; IPCC 2008). This strategy represents an increase in water surface, which, together with future increases in the evaporation rate, could result in additional water losses. This loss could counterbalance other positive effects of increasing water storage in the basin water balance, resulting in even less water availability for very stressed basins.

References

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T, Siebert S (2003) Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. Hydrol Sci J 48:339–348

Alcamo J, Flörke M, Marker M (2007) Future long-term changes in global water resources driven by socio-economic and climatic change. Hydrol Sci J 52:247–275

Amini Fasakhodi A, Nouri SH, Amini M (2010) Water resources sustainability and optimal cropping pattern in farming systems; a multi-objective fractional goal programming approach. Water Resour Manag 24 (15):4639–4657

Barnes GT (2008) The potential of monolayers to reduce the evaporation of water from large water storages. Agric Water Manag 95:339–353

Brown JAH (1988) The potential for reducing open water evaporation losses: a review. Hydrology and water resources symposium. ANU, Camberra, pp 108–115

Calatrava J, Martínez-Granados D (2012) El valor de uso del agua en el regadío de la cuenca del Segura y en las zonas regables del trasvase Tajo-Segura. Econ Agrar Recur Naturales 12(1):5–32

Carmona G, Varela-Ortega C, Bromley J (2011) The use of participatory object-oriented Bayesian networks and agro-economic models for groundwater management in Spain. Water Resour Manag 25:1509–1524

Christodoulou SE (2011) Water resources conservancy and risk reduction under climatic instability. Water Resour Manag 25:1059–1062

CHS (2007) Estudio General sobre la Demarcación Hidrográfica del Segura. Confederación Hidrográfica del Segura, Murcia

Craig I, Green A, Scobie M, Schmidt E (2005) Controlling evaporation loss from water storages. NCEA Publication No. 1000580/1, Queensland, Australia

Getirana ACV, Malta VF, Azevedo JPS (2008) Decision process in a water use conflict in Brazil. Water Resour Manag 22:103–118

Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. Glob Planet Chang 63:90–104

Gökbulak F, Özhan S (2006) Water loss through evaporation from water surfaces of lakes and reservoirs in Turkey. E-water: official publication of the European Water Association [on line]. http://www.ewaonline.de. ISSN 1994-8549

Gupta V, Tadros M, Bradshaw RW, Showalter SK, Miller JE, Evans L, Sasaki DY (2002) Progress report: advanced concepts group Fy01-1362-LDRD, solutions to national and global security issues based on limited freshwater resources. SAND2002-0781. Sandia National Laboratories, Albuquerque, NM

Iglesias A (2009) Policy issues related to climate change in Spain. In: Dinar A, Albiac J (eds) Policy and strategic behaviour in water resource management. Earthscan, London, United Kingdom. ISBN: 978-1-84407-669-7

Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour Manag 21(5):775–788

IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 976

IPCC (2008) Climate change and water technical paper of the intergovernmental panel on climate change. IPCC Secretariat, Geneva, p 210

Jurak D (1989) Effect of climate change on evaporation and water temperature. Proc Conf Clim Water Helsinki I:138–148

Krol MS, de Vries MJ, van Oel PR, Araújo JC (2011) Sustainability of small reservoirs and large scale water availability under current conditions and climate change. Water Resour Manag 25:3017–3026

Lowe LD, Webb JA, Nathan RJ, Etchells T, Malano HM (2009) Evaporation from water supply reservoirs: an assessment of uncertainty. J Hydrol 376:261–274

Martínez-Alvarez V, González-Real MM, Baille A, Molina Martínez JM (2007) A novel approach for estimating the pan coefficient of irrigation water reservoirs. Application to South Eastern Spain. Agric Water Manag 92:29–40

Martínez-Alvarez V, González-Real MM, Baille A, Maestre Valero JF, Gallego Elvira B (2008) Regional assessment of evaporation from agricultural irrigation reservoirs in a semiarid climate. Agric Water Manag 95:1056–1066

Martínez-Alvarez V, Maestre Valero JF, Martín Górriz B, Gallego Elvira B (2010) Experimental assessment of shade-cloth covers on agricultural reservoirs for irrigation in South-Eastern Spain. Span J Agric Res 8 (S2):122–133

Martínez-Granados D, Maestre-Valero JF, Calatrava J, Martínez-Alvarez V (2011) The economic impact of water evaporation losses from water reservoirs in the Segura basin, SE Spain. Water Resour Manag 25:3153–3175

MED WS&D WG (2007) Mediterranean water scarcity and drought report. Mediterranean water scarcity & drought working group, European Commission Technical Report 009-2007. www.emwis.net/topics/WaterScarcity

Menzel L, Matovelle A (2010) Current state and future development of blue water availability and blue water demand: a view at seven case studies. J Hydrol 384:245–263

MIMAM (2000) Libro blanco del agua en España. Ministerio de Medio Ambiente, Madrid

MIMAM (2001) Plan Hidrológico Nacional. Ministerio de Medio Ambiente, Madrid

Moreno JM et al (2005) Evaluación preliminar de los impactos en España del Cambio Climático. Ministerio de Medio Ambiente, Madrid

Opricovic S (2009) A compromise solution in water resources planning. Water Resour Manag 23:1549–1561

Regulwar DG, Gurav JB (2011) Irrigation planning under uncertainty - a multi objective fuzzy linear programming approach. Water Resour Manag 25(5):1387–1416

Santos FD, Forbes K, Moita R (2002) Climate change in Portugal: scenarios: impacts and adaptation measures. SIAM project report. Gradiva, Lisbon

Schindler DW, Donahue WF (2006) An impending water crisis in Canada's western prairie provinces. Proc Natl Acad Sci USA (PNAS) 103:7210–7216

Schröter D, Cramer W, Leemans R, Prentice IC, Araújo MB, Arnell NW, Bondeau A, Bugmann H, Carter TR, Gracia CA, de la Vega-Leinert AC, Erhard M, Ewert F, Glendining M, House JI, Kankaanpää S, Klein RTJ, Lavorell S, Linder M, Metzger MJ, Meyer J, Mitchell TD, Reginster I, Rounsevell M, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MT, Thonicke K, Thuiller W, Tuck G, Zaehle S, Zierl B (2005) Ecosystem service supply and vulnerability to global change in Europe. Science 310:1333–1337

Segal L, Burstein L (2010) Retardation of water evaporation by a protective float. Water Resour Manag 24:129–137

Trenberth KE, Dai AG, Rasmussen RM, Parsons DB (2003) The changing character of precipitation. Bull Am Meteorol Soc 84:1205–1217

Tsakiris G, Spiliotis M (2011) Planning against long term water scarcity: a fuzzy multicriteria approach. Water Resour Manag 25:1103–1129

Wang J, Cheng G, Gao Y, Long A, Xu Z, Li X, Chen H, Barker T (2008) Optimal water resource allocation in arid and semi-arid areas. Water Resour Manag 22:239–258

Ward FA (1987) Economics of water allocation to instream uses in a fully appropriated river basin: evidence from a New Mexico wild river. Water Resour Res 23:381–392

Young RA (2005) Determining the economic value of water: concepts and methods. RFF Press, Washington