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Experimental assessment of shade-cloth covers on agricultural reservoirs for irrigation in south-eastern Spain

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Abstract

Agricultural water reservoirs (AWRs) are commonly used to guarantee water supply throughout the whole irrigation season in arid and semiarid areas. An important fraction of the total stored water is lost through evaporation, substantially decreasing overall irrigation efficiency. In this study, the effects of suspended shade cloth covers (SSCCs) on reducing evaporation and on the quality of the stored water have been experimentally assessed. To this aim, an AWR located in south-eastern Spain was monitored during two consecutive years. During the first year, the AWR remained uncovered, while during the second year it was covered with a black polyethylene SSCC. The evaporation rate, the water temperature profile and the driving meteorological variables determining evaporation were measured to assess the technical viability of the cover. Evaporation measurements for covered conditions were compared with estimations obtained from an open-water evaporation model which was validated during the first year of experimentation. A reduction close to 85% in the evaporation rate was found. To assess the effects on water quality, water samples and measurements with a multiparametric instrument were monthly collected during the two-year experimental period. Electrical conductivity, chlorophyll concentration and turbidity were measured using this equipment. Results indicate that the reduction in solar radiation (1% transmission through the cover) dramatically reduced the photosynthetic activity; hence algal bloom was highly limited. Finally, the main benefits and costs associated with the cover installation were identified in order to analyse economic viability under different scenarios representative of the current irrigated farming situation in south-eastern Spain.

Additional key words: algae concentration; economic viability; electrical conductivity; evaporation; polyethylene meshes; water saving.

Resumen

Evaluación experimental de la aplicación de coberturas de sombreo en balsas

En las regiones áridas y semiáridas, las balsas son una instalación común para garantizar el suministro de agua para riego. Las balsas experimentan importantes pérdidas de agua por evaporación que afectan a la eficiencia de riego. Este estudio analiza los efectos de la instalación de coberturas de sombreo suspendidas (CSSs) sobre la evaporación y la calidad del agua para riego. Durante dos años se monitorizó una balsa ubicada en el sureste español. El primer año la balsa permaneció descubierta, mientras que el segundo año se cubrió con una CSS de textil de polietileno negro. Para determinar la viabilidad técnica se midieron la evaporación, el perfil térmico del agua y las principales variables meteorológicas. La evaporación registrada en la balsa cubierta durante el segundo año se comparó con la estimada mediante un modelo de evaporación en lámina libre, validado durante el primer año. Se obtuvo una reducción de la evaporación próxima al 85%. Para determinar los efectos sobre la calidad del agua, mensualmente se recogieron muestras y se realizaron sondeos en profundidad con una sonda multiparamétrica. Se determinó la conductividad eléctrica, la concentración de clorofila y la turbidez. Los resultados indican una elevada reducción de la actividad fotosintética y del crecimiento de algas como consecuencia de la baja transmisión de radiación solar a través de la cobertura (menos del 1%). Finalmente, se identificaron y valoraron los principales costes y beneficios de la instalación de la cobertura con el fin de analizar su viabilidad económica en el sureste español.

Palabras clave adicionales: ahorro de agua; concentración de algas; conductividad eléctrica; evaporación, textiles de polietileno; viabilidad económica.

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Abbreviations used: AWR (agricultural water reservoir), EC (electrical conductivity), IRR (internal rate of return), NPV (net present value), NTU (nefelometric turbidity unit), RMSE (root mean square error), SSCC (suspended shade cloth cover), SRB (Segura river basin).

Introduction

In arid and semi-arid regions, where water is scarce and its availability varies seasonally, Agricultural Water Reservoirs (AWRs) for irrigation are commonly used to guarantee water supply throughout the whole irrigation season (Daigo and Phaovattana, 1999; Martínez Alvarez *et al*., 2006; Ali *et al*., 2008). Evaporation losses substantially decrease reservoir storage efficiency, particularly during periods with high solar radiation and high vapour pressure deficit. In the semi-arid Segura River Basin (SRB; south-eastern Spain), Martínez Álvarez *et al*. (2008) estimated that the evaporation water loss from AWRs represents 8.3% of the irrigation water use on a regional scale. The volumetric magnitude of these losses (58.5 hm^3) is equivalent to 27% of the total urban water consumption for this region with approximately two million inhabitants. Craig *et al*. (2005) estimated that in many areas of Australia, up to 40% of the water stored in on-farm reservoirs can be lost to evaporation. These figures indicate that in regions facing water shortages, the implementation of techniques to reduce evaporation from AWRs is as important as promoting highly efficient on-farm irrigation systems and techniques.

A wide variety of methods are available to mitigate evaporation from AWRs, all of which can be classified into the following groups: physical, operational, chemical and structural methods (Brown, 1988). Physical methods reduce evaporation by altering the properties of the water body. This is the case of destratification (*i.e.* artificial overturning of a stratified water profile) (Koberg and Ford, 1965) or changing the water colour to modify the albedo (Cooley, 1983). Operational methods refer to improving the management of a set of reservoirs, so that one or more of them are completely full, while the rest store lower water levels at higher temperatures (*i.e.* higher evaporation rates). Chemical methods mainly involve the use of monolayers, such us cetyl alcohol or stearyl alcohol, which spontaneously self-spread over the water surface and create a film one molecule thick. Monolayers usually provide moderate evaporation reductions (10-40%) (Craig *et al*., 2005). However, they are a low-cost measure best suited to large AWRs (> 10 ha in area). In practice, monolayer performance can be negatively affected by disruption of the chemical layer by dust particles, negative interactions with dam bacteria and/or product displacement by wind dragging (Barnes, 2008). The last group, structural methods, includes physical structures like floating materials to minimize energy and mass exchanges between the water surface and the surrounding air (Daigo and Phaovattana, 1999), shelters that protect the water body from wind (Hipsey and Sivapalan, 2003) or shading screens which minimise the incoming radiation and wind speed over the water surface.

Among the structural methods, suspended shade cloth covers (SSCCs) have been pointed out as one of the most promising techniques from a technical point of view (Craig *et al*., 2005; Martínez Álvarez *et al*., 2006). Craig *et al*. (2005) evaluated the efficiency of a porous shade cover on a shallow dam (3.8 ha, 3 m depth) located in south-eastern Queensland (Australia), where the evaporative demand is very high (2,200 mm $year^{-1}$). They achieved evaporation reductions up to 87% for summer months. In southern Spain, Martínez Álvarez *et al*. (2006) carried out an assessment on different shade cloth materials for minimizing evaporation from Class-A pans. The double black polyethylene cloth was found to be the most effective, achieving 83.5% reduction in evaporation at a tank scale.

Apart from mitigating evaporation, the installation of SSCCs has a positive effect on the quality of the stored water (Craig *et al*., 2005; Finn and Barnes, 2007). The SSCC minimizes solar radiation and hence algae growth, which is a very problematic issue for drip irrigation systems (Ravina *et al*., 1992; Karico, 2000). The SSCC also limits the entry of wind-borne dust and debris into the reservoir. It was also found that the SSCC allows the majority of rainfall to be captured in the dam. This can decrease salt concentration when the rainfall minus evaporation balance is positive.

The final decision of whether to install a structure of this kind under a particular set of farming conditions should be based on a cost/benefit analysis. To date, few studies have been specifically devoted to determining the economic viability of such investments. Craig *et al*. (2005) and Watts (2005) identified a number of areas for further research in the field of evaporation reducing techniques in AWRs, highlighting the importance of developing studies aimed at the assessment of their economic viability under specific farm conditions.

Considering the previous works, it seems that SSCCs can be a very efficient way to tackle evaporation losses in climates with high evaporative demand. Therefore, a detailed study on the performance of shade meshes at AWR scale and an assessment of its effect on stored water quality were carried out. In addition, the economic viability of SSCCs under different scenarios representative of the current farming situation in south-eastern Spain is analyzed.

Material and methods

AWR and cover description

The experimental AWR is located at the Agricultural Experimental Station of the Technical University of Cartagena, south-eastern Spain (37°35'N, 0°59'W). The area is characterized by a Mediterranean semiarid climate, with warm and dry summers and mild winter conditions. Annual rainfall averages 350 mm, with high seasonal and inter-annual variability; most precipitation occurs during the fall and winter months. Class-A pan evaporation ranges from 1,600 to 2,000 mm year^{-1}.

The AWR considered in this study can be considered typical in the SRB. It has a top area of 2,400 m^2 (rectangular, 55 × 44 m), a depth of 5 m and an inner slope of 1/1 in the earthwork embankments. This geometry results in a storing capacity of 11,920 m^3. Seepage through walls and bottom is minimized by means of waterproof layers. About 32% of the existing AWRs in the SRB have similar capacity and dimensions (Martínez Álvarez *et al.*, 2008). This type of AWR usually serves farms with an area of 4-5 ha.

Prior to the experimental campaign, the AWR was filled with water from the Tajo-Segura Aqueduct, a water transfer system to the SRB. During the two-year experimental period (from April 2007 to April 2009), the reservoir was not used for irrigation purposes, and there were just two refills: the first one was performed in September 2007 to compensate for summer evaporation, and the second was performed prior to the AWR covering in April 2008. These refills did not significantly affect the thermal evolution of the water body since the temperature of the added water was similar to that of the stored water.

In April 2008, the SSCC was installed on the AWR. The shade cover consists of a porous cloth suspended above the water surface by means of a high tension polyamide cable structure. The cloth is a double layer mesh made of black polyethylene fabric (Atarsun, Atarfil S.L.). The cables are both above and below the cloth to hold the mesh and to prevent wind suction. The structure spans from one bank to the other without any intermediate posts, as the maximum breadth of the AWR is moderate (55 m).

Evaporation, water temperature and meteorological data collection

During the first year of experimentation (from April 2007 to April 2008), the AWR remained uncovered. The evaporation rate, the meteorological variables and the water temperature profile were continuously registered. The experimental design is depicted in Figure 1.

The evaporation rate, *E*, was obtained from water level measurements performed with a pressure transducer (PDCR1830, Druck, UK) with an accuracy of ± 0.06% over a 7.5 kPa range. The water level sensor was placed in a vertical polyethylene pipe communicated with the AWR. Measurements corresponding to rainy days were omitted in the study since the variation of level corresponding to rainfall and to evaporation could not be differentiated.

Water temperature measurements were conducted with temperature sensors (T-107, Campbell Scientific Inc, USA) submerged in the water from a floating raft. Seven temperature probes were used to produce a tem-

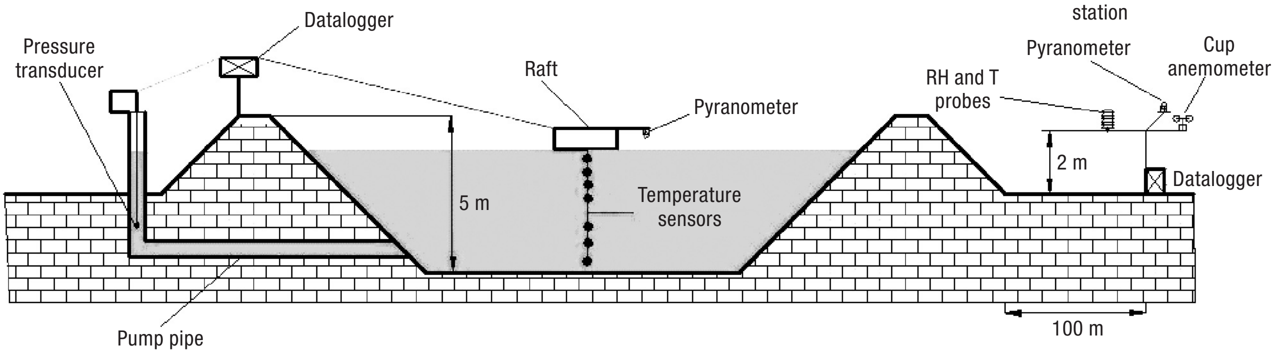

Figure 1. Experimental design in the uncovered AWR. RH and T are air relative humidity and temperature respectively.

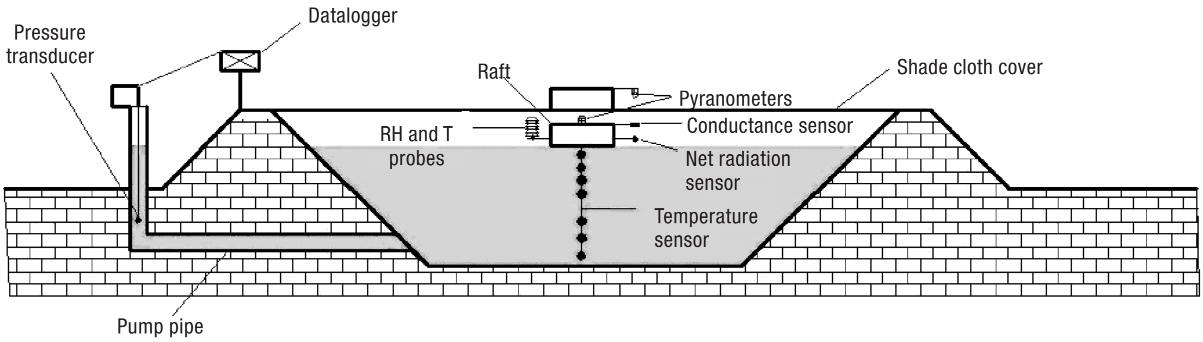

Figure 2. Experimental design in the covered AWR. RH and T are air relative humidity and temperature respectively.

perature profile. Probes were located at the following depths: surface (T_{w0}), 0.33 m (T_{w033}), 0.66 m (T_{w066}), 1 m (T_{w1}), 2 m (T_{w2}), 3 m (T_{w3}) and 4 m (T_{w4}).

Meteorological variables were continuously measured at an elevation of 2 m aboveground. An automated meteorological station located in the vicinity of the AWR was used for this purpose. A programmable datalogger (CR1000, Campbell Scientific Inc., USA) controlled sensors for air temperature, T_a, and relative humidity, RH (HMP45C probe, Vaisala, Finland), solar radiation, R_s (CMP 11, Kipp & Zonnen B.V., The Netherlands), incoming long-wave radiation, L_a (Kipp & Zonnen CGR 3 pyrgeometer), wind speed, U (A100R, Vector Instruments, UK) and total precipitation (tipping bucket rain gauge, type 52203, RM Young Inc., Traverse City, USA). A similar data colleting procedure was used during the second year of experimentation (from April 2008 to April 2009). The evaporation rate of the covered AWR, E_C, and the water temperature profile were continuously recorded. Additional sensors were used to measure the meteorological conditions above and below the cover (Fig. 2).

The reflected shortwave radiation was measured 0.25 m above the cover with an inverted pyranometer (CMP 6, Kipp & Zonnen) assembled on a steel structure. This information was used to determine the SSCC albedo. Below the mesh and 0.30 m above the water surface, several meteorological sensors were implemented on a metallic structure attached to the raft to register air temperature, T_{aC}, and relative humidity, RH_C (HMP45C probe, Vaisala), wind speed, U_C, (UPCT BLC-Y wind speed prototype sensor), transmitted solar radiation, R_{sC} (CMP 11, Kipp & Zonnen) and net radiation, R_{nC} (NRLITE, Kipp & Zonnen). All sensors were scanned at 10 s intervals, hourly averaged and registered by automatic dataloggers. The sensors were periodically calibrated.

Water quality data collection

During the two years of experimentation, water samples from the AWR were monthly collected at depths of 1, 2, 3 and 4 m. Samples (250 mL) were driven to the laboratory in a portable cooler, where they were fixed with formalin. The concentration of algae cells was determined using an inverted microscope. In addition, a multiparametric instrument (YSI Incorporated, USA) was used to measure in situ the electrical conductivity (EC) profiles, chlorophyll, and turbidity in the AWR.

Open water evaporation model for the uncovered AWR

In order to determine the evaporation reduction coefficient associated to the use of the SSCC, an accurate estimation of the open-water evaporation is required. A physical model based on the energy budget of the water body was applied to estimate evaporation during the second experimental year if the AWR had been uncovered. The model determines daily evaporation and water temperature from the main meteorological data assuming isothermal behaviour of the AWR (*i.e.* thermal stratification is not considered). Water measurements conducted in the experimental AWR during the first year of experimentation showed a homogeneous water temperature profile during most of the year. Slight stratification (2°C) was only observed in spring and early summer. Therefore, it can be assumed that for uncovered conditions the water body is well-mixed and the water temperature profile is homogeneous. Considering the latter hypothesis, and neglecting heat transmission through the bottom and side walls and the energy advected by inflows, the energy balance in the water body can be expressed as follows:

$$R_n - \lambda E + Q_w + H = 0 \quad [1]$$

where R_n is the net radiation of the water surface, λE is the latent heat flux, Q_w the heat storage in the water body and H the sensible heat exchanged between the air and the water surface. All fluxes are in MJ m^{-2} day^{-1}, with E being the evaporation rate in kg m^{-2} day^{-1} (*i.e.* in mm day^{-1}) and λ the latent heat of vaporization in MJ kg^{-1}.

Net radiation reflects the balance of incoming and outgoing short-wave and long-wave radiation at the water surface:

$$R_n = (1-\alpha)\ R_s + L_a - L_w \quad [2]$$

where α is the albedo of the water, and L_a and L_w are the downward and upward long-wave radiation respectively. Monthly values of albedo measurements were used. L_w was calculated with the Stefan-Boltzmann law, considering the water emissivity to be 0.97 (Ali *et al.*, 2008).

The latent heat flux was obtained with a calibrated mass transfer equation:

$$E = h_v \left(e_s - e_a\right) \quad [3]$$

where e_s (kPa) is the saturated water vapour pressure at the surface temperature T_w, e_a (kPa) is the actual vapour pressure of the air and h_v (mm day^{-1} kPa^{-1}) is the daily-average convective coefficient for water vapour transfer. To calibrate h_v, evaporation measurements collected in 2007 were used (Gallego-Elvira *et al.*, 2010).

The heat storage was calculated by means of the following expression:

$$Q_w = C_w\ z \frac{\Delta T_w}{\Delta t} \quad [4]$$

where C_w (J m^{-3} °C^{-1}) is the volumetric heat capacity of water at the temperature T_w, z (m) stands for the reservoir depth and ΔT_w is the change in water temperature (°C) occurring during a time step ($\Delta t = 1$ day).

The sensible heat exchange at the reservoir interface air-water was calculated assuming an analogy between mass and energy transfer:

$$H_s = h_c \left(T_a - T_w\right) \quad [5]$$

$$h_c = \lambda \gamma h_v \quad [6]$$

where h_c is the daily-average coefficient of convective heat exchange (MJ m^{-2} K^{-1} day^{-1}) and γ is the psychometric constant (kPa K^{-1}).

All terms in Eq. [1] depend on water temperature, T_w. Basically, the model operates at a daily time step iterating the water temperature until the equilibrium condition of the energy balance is found.

Economic assessment

Factors affecting the benefits and costs

We conducted a discounted cash flow analysis to assess the costs (capital, operation and maintenance) and benefits (water saved and water quality effects), of installing a shade cover on the experimental AWR. The technical data is derived mainly from this research, whereas the economic data has been gathered during discussions with both SSCC suppliers and users. The economic viability of the investment was analysed to determine Net Present Value (NPV, €) and Internal Rate of Return (IRR, %).

To assess the benefits, an evaporation reduction factor of 84% was chosen according to the experimental results reported in this paper. The value of the conserved water was determined under two scenarios: (1) regular water supply, valuing conserved water at its purchasing price, and (2) insufficient water supply, making it impossible to cultivate the total farm area. In the first case, the price of water in the SRB depends on its origin. Representative values are €0.15 m^{-3} for surface water, €0.30 m^{-3} for ground water and €0.50 m^{-3} for desalinized sea water. In the second case, conserved water would increase the crop area and therefore it can be valued in terms of the net margin associated to each m^3 of water consumed on the farm.

Due to the positive effects of the SSCCs on water quality, a reduction in filtration close to 90% was selected in this study, based on several personal communications from landowners. Two percentage values of the water for irrigation depending on the stored water quality were established for filter cleaning in the study. In the first case —0% of the water for irrigation— there is no need for filter cleaning and all water is devoted to irrigation. In the second case, 3% of the irrigation water is devoted to filter cleaning.

Finally, the SSCC cost refers to the capital cost (€) of the entire cover (shade-cloth plus structure) at installation time. This cost significantly varies depending on installation specifics, such as site location, access, wind, storage geometry, and surface area. In spite of such cost variability, product suppliers indicate a representative cost of €7.80 m^{-2} (€5.30 m^{-2} corresponding to the structure and €2.50 m^{-2} to the shade-cloth). Operation and maintenance costs were very low and therefore neglected. These costs are in fact counterbalanced by small additional benefits such as the increase of the waterproof membrane lifespan and/or lowering remedial action with respect to algae (such as algaecide dosing).

Studied scenarios and general assumptions

Multiple scenarios were analysed taking into account the influence on the economic indicators NPV and IRR. They are as follows: (1) three levels of Class-A pan evaporation (1,600, 1,800 and 2,000 mm year^{-1}), (2) the unit water value ranging from €0.1 to 5 m^{-3}, covering the cost of purchasing the water and the net margin per m^3 of the most representative crops in the SRB, and (3) two levels of cleaning filtering requirements (0 and 3% of the irrigation water).

To simplify the economic assessment, the following general assumptions were established:

— 90% of rainfall on the surface of the storage is effectively collected.

— A discount rate of 5% was assumed in calculating economic indicators.

— An interest rate of 5% was assumed in calculating the financing of the invested capital.

— Structural lifespan was assumed to be 30 years.

— Shade-cloth lifespan was assumed to be 15 years.

— The investment value at the end of the SSCC life is zero.

Results and discussion

Prediction of open-water evaporation

The daily evaporation and water temperature measurements collected during 2007 were used to calibrate and validate the open-water evaporation model described above. A detailed description of the calibration process can be found in Gallego-Elvira *et al*. (2010). Table 1 summarizes the performance of the model. Following calibration, the model provides accurate estimates of the evaporation rate (Root Mean Square Error, RMSE = 0.52 mm day^{-1}) and water temperature (RMSE = 0.25°C)

Effects of the cover on evaporation and water temperature

During the one-year measurement period in the covered AWR, a total decrease of water level of E_C = 191.6 mm was observed, while the predicted total evaporation for uncovered conditions was E = 1,191 mm. Therefore, the polyethylene mesh achieved an annual evaporation reduction factor ($F_R = 1\text{-}E_C/E$) of 84%, similar to the one found by Martínez Álvarez *et al*. (2006) in previous trials with Class-A evaporation pans.

The evolution of the daily evaporated water depth for covered (E_C) and uncovered (E) conditions is depicted in Figure 3a. The efficiency of the cover on mitigating evaporation presented relevant seasonal variation. From the daily values of E_C and E, the mean monthly reduction factors were derived (Table 2). It can be observed that for the warm season (Jun-Aug), when the evaporative demand is very high (representing more than 50% of annual E rate), F_R reaches the maximum value (90.1%) without a significant daily variation (SD = ± 2.3%). This fact is partly related to the high mesh efficiency on minimizing the available radiative energy (*i.e.* net radiation) for the evaporation process.

The evolution of the water temperature profile for the uncovered and covered AWR is presented in Figure 3b. Only one water temperature, T_w, is given for uncovered conditions, since the water profile was observed to be quasi-isothermal. Following the installa-

Table 1. Summary of the model performance on estimating evaporation an water temperature

Estimated variable	RMSE	MBE	MAE	ME (%)	Regression parameters		
					R^2	Slope	Intercept
Evaporation (mm day^{-1})	0.52	0.07	0.35	94.3	0.95	1.03	–0.22
Water temperature (°C)	0.25	–0.30	0.33	99.5	0.99	0.99	0.37

RMSE: root mean squared error. MBE: mean bias error. MAE: mean absolute error. ME: model efficiency.

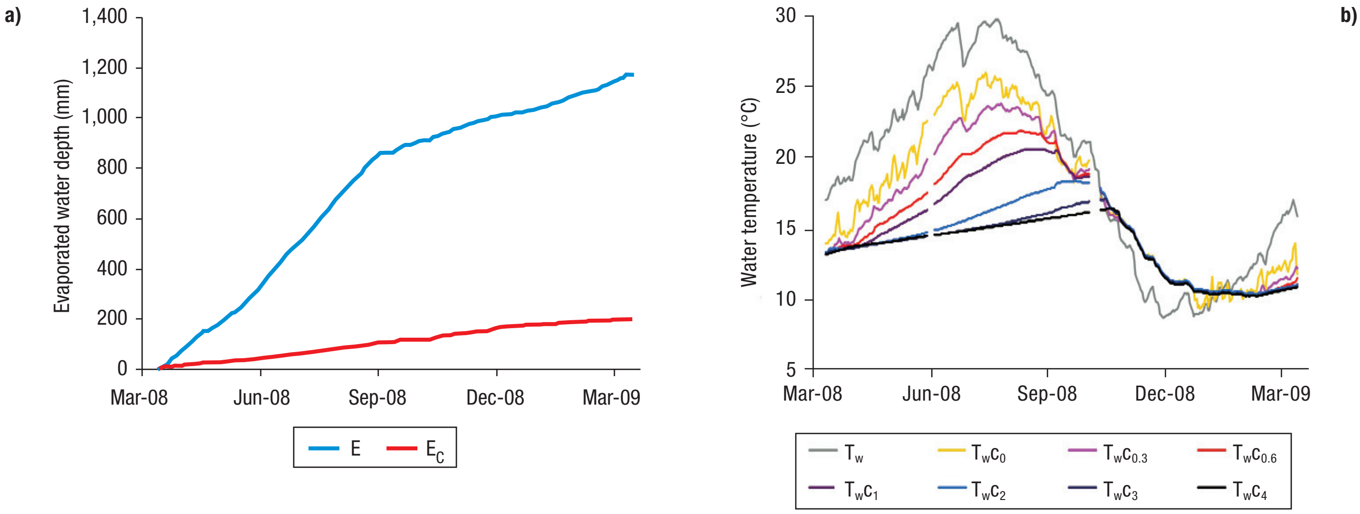

Figure 3. Annual evolution of (a) evaporated water depth and (b) water temperature profile for covered and uncovered conditions. E and E_c are the evaporation rate for uncovered and covered conditions respectively. T_w is the water temperature for uncovered conditions and T_{wCi} are the water temperature for covered conditions at the depth i (m).

tion of the SSCC, the intensity of the mixing process due to the wind stirring effect dramatically diminished: water became stratified for most of the year. The maximum temperature gradient was observed at the beginning of August, when the temperature difference (from surface to bottom) reached 11°C. The overturning took place in November, following heavy rainfall events, and water temperature profile remained homogeneous until January. In general, T_w in the covered AWR was lower than in the uncovered, with the exception of the three-month period following the overturning (Nov-Jan), when deeper layers contributed to heat the water surface. For the latter period (isothermal conditions) F_R presented the lowest values (Table 2), but note that these months also presented the lowest evaporative demand and thus the global F_R was less affected.

SSCC effects on meteorological variables

Figure 4 presents the evolution of the main meteorological variables measured below the cover and in

Table 2. Annual and monthly evaporation with (E_C) and without the cover (E), relative importance of monthly evaporation with respect to the annual value and evaporation reduction factors (F_R)

Month	E_C (mm)	E (mm)	% of annual E	F_R (%)	SD
April-08	15.47	112.36	0.09	85.7	±6.3
May-08	12.07	110.27	0.09	89.1	±3.4
Jun-08	17.69	168.02	0.14	89.0	±2.8
July-08	19.54	175.84	0.15	88.8	±2.2
August-08	18.58	187.90	0.16	90.1	±2.3
September-08	19.87	110.93	0.09	82.8	±10.8
October-08	15.88	79.28	0.07	82.9	±19.6
November-08	22.48	54.46	0.05	60.8	±24.9
December-09	23.91	39.63	0.03	38.4	±32.0
January-09	11.95	41.67	0.03	70.2	±23.0
February -09	9.49	47.25	0.04	80.4	±14.5
March-09	4.67	63.37	0.05	93.0	±6.6
Annual	191.59	1,190.98	—	84.1	—

SD: standard deviation.

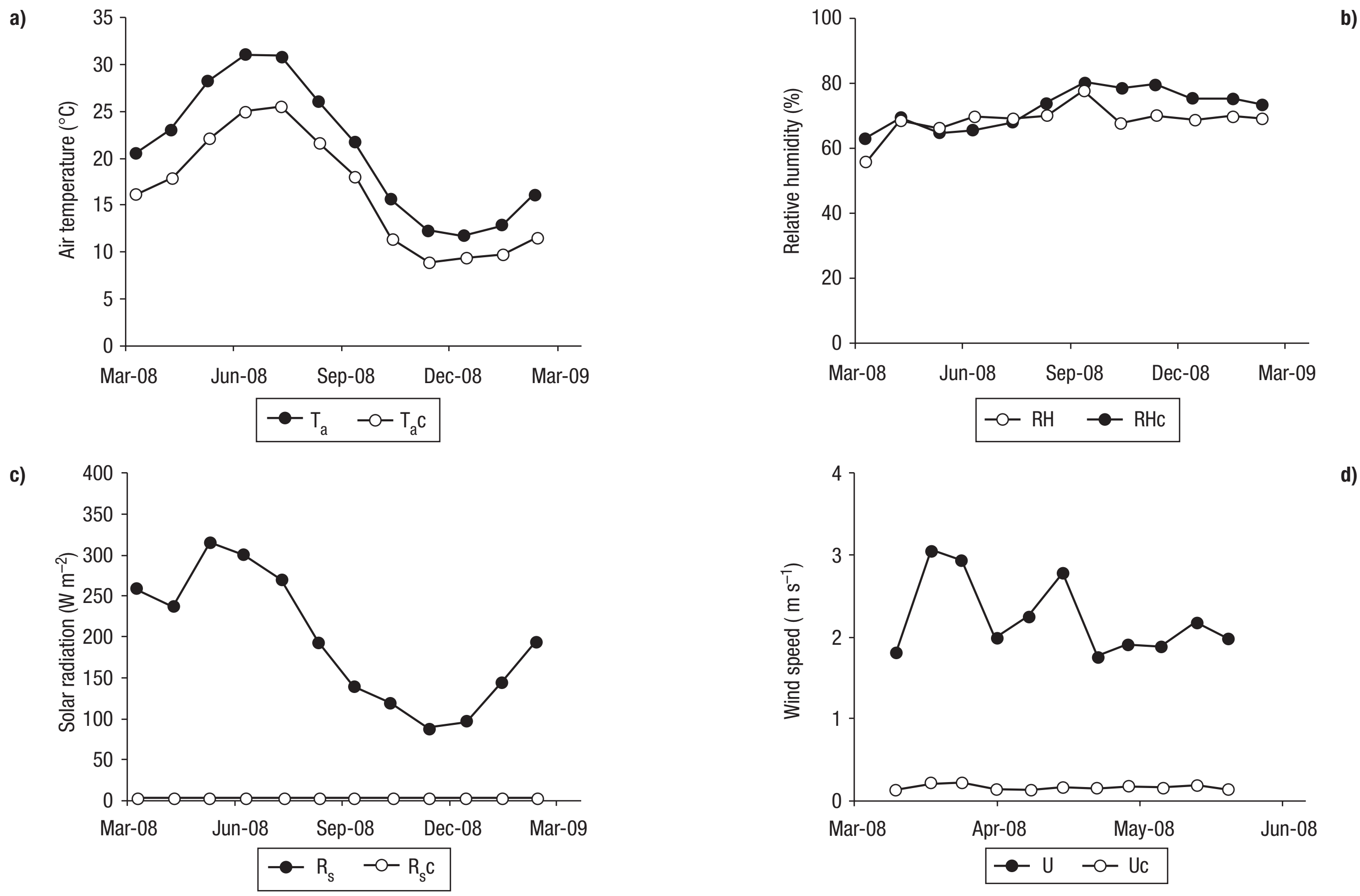

Figure 4. Comparison of the meteorological variables measured below the cover and 2 m aboveground. Monthly values of a) air temperature (T_a and T_{aC}), b) relative humidity (RH and RH_C), c) solar radiation (R_s and R_{sC}), and d) weekly values of wind speed (U and U_c).

the meteorological station. Monthly values are presented for all variables except for the wind speed, which is depicted on a weekly scale since this variable was measured from April 2008 to June 2008. The air temperature below the mesh (Fig. 4a) remained on average 5°C above the outside air temperature, whereas the relative humidity (Fig. 4b) did not show a relevant difference for the shaded and normal conditions. Thus, the vapour pressure of the outside ambient air, e_a, was markedly lower than under the mesh, e_{aC}. Figure 4c shows the low solar radiation transmission of the cover, less than 1% for the whole year. The cover mainly absorbed the incoming solar radiation (percentage of absorbed R_s: 91.2 ± 1.7%), presenting very low values of reflectivity (8.2 ± 2.3%) and transmissivity (0.4 ± 0.1%). During the period with wind records, wind speed at the station varied from 1.2 to 6.4 m s^{-1} on a daily scale, while wind speed below the mesh remained within the range 0.1-0.4 m s^{-1}. On weekly averages (Fig. 4d), U_C had a rather constant value (around 0.2 m s^{-1}), regardless of the value of U, which varied from 1.7 to 3.1 m s^{-1}. Overall, these observations indicate that for the observed wind speed range the cover provided a strong sheltering effect (reduction factor = 91.8%), slightly affected by the fluctuations of wind speed.

The presence of the cover substantially affected the radiative and aerodynamic exchanges from the water surface to the surrounding air. In order to assess the influence of the mesh on the evaporation rate, two aspects need to be analysed. First, the evaporation driving force, which with wind speed determines the aerodynamic exchanges under the cover, and second, the radiative balance at the water surface, looking into the reduction of net radiation caused by the cover. The driving forces of evaporation for uncovered ($\Delta e = e_w - e_a$) and covered ($\Delta e_C = e_{wC} - e_{aC}$) conditions are presented in Figure 5a. The overall lower water surface temperature (Fig. 3b) and higher air temperature with no relevant variation in relative humidity (Figs. 4a and 4b) led to a marked decrease of the covered evaporation driving

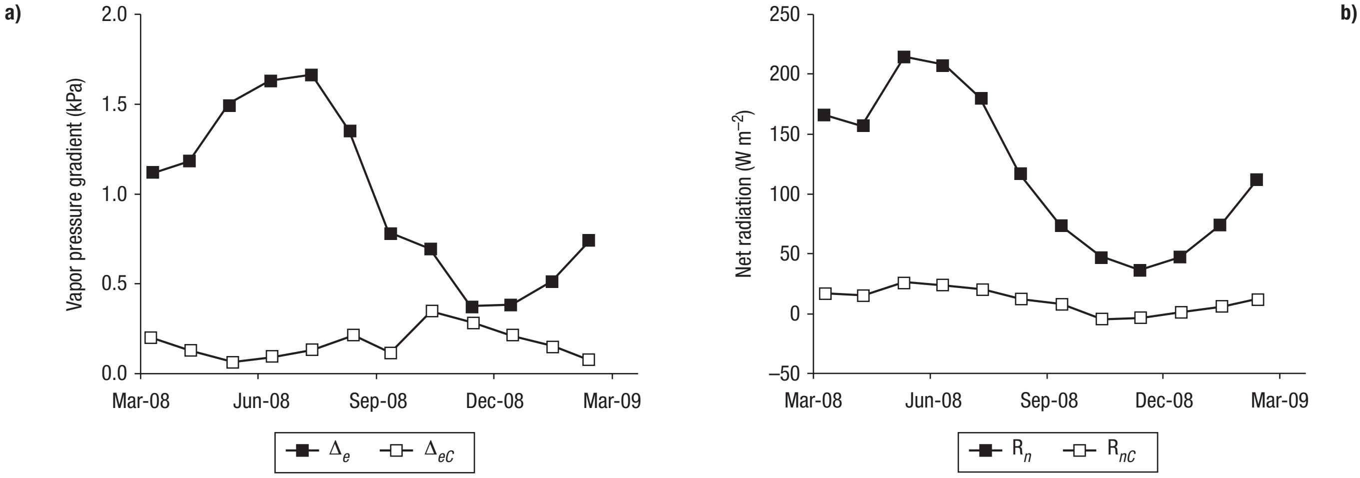

Figure 5. Annual evolution of monthly averages of (a) evaporation driving force for open-water (Δ_e) and shaded conditions (Δ_{eC}), and (b) modelled open-water net radiation (R_n) and measured net radiation under the cover (R_{nC}).

force with respect to uncovered conditions. This reduction in the evaporation driving force is partly due to the reduction in net radiation induced by the cover, which depends on the mesh optical properties. Monthly averages of modelled net radiation for free-water surface conditions (R_n) and measured net radiation below the mesh (R_{nC}) are presented in Figure 5b. Note that for the high evaporative demand period (Jun-Aug), R_{nC} corresponds just to 12 % of R_n.

Apart from modifying the microclimate to the reduce evaporation, SSCCs have to be permeable to rain. The experimental shade cloth allowed the majority of the rainfall to be stored in the reservoir. The rain gauge recorded a total water height of 576 mm for the experimental period, while a water level increase corresponding to rainfall of 524 mm was registered. These observations indicate that 90% of the rainfall was stored. The mean permeability derived from daily rain events, 83.1%, was lower than the latter figure. This is related to the low daily values of permeability observed on days with light rainfalls (< 5 mm). When light rains fell on the cover, an important part of water was evaporated (permeability values < 70%), particularly if the rain event occurred in the afternoon when the cover temperature was very high.

SSCC effects on water quality

Electrical conductivity

Figure 6 shows the evolution of EC (average profile depth measurements) in the AWR for uncovered and covered conditions. During the first year of experimentation, the AWR stayed uncovered and the balance of evaporation minus rainfall was positive (1,331.7 mm of evaporation *versus* 554.8 mm of rainfall) leading to an average increase in EC of 14.23%. In the second year, when the AWR was covered, the water balance was positive to rainfall (rainfall = 441.2 mm and evaporation = 191.6 mm), resulting in a 6.59% reduction of EC.

Chlorophyll concentration

Chlorophyll concentration is widely used as a standard method of estimating phytoplankton (algal) biomass (Wetzel, 2001). Figure 7 presents the evolution

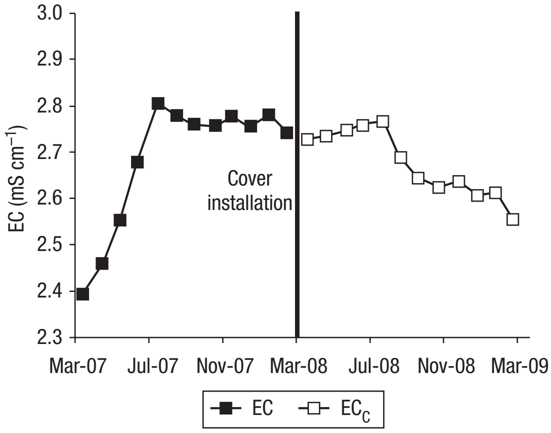

Figure 6. Average profile of electrical conductivity measurements in the AWR for uncovered (EC) and covered (EC_C) conditions.

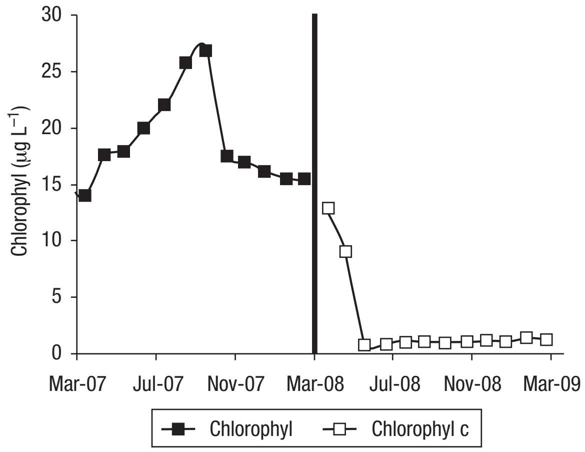

Figure 7. Average profile of chlorophyll concentration measurements in the AWR for uncovered and covered (*C* subscript) conditions.

of chlorophyll concentration (average profile depth measurements) for the two-year experimentation period. The low levels of solar radiation below the cover induced a massive reduction of the photosynthesis from the living algae in the AWR. A 90% filtration reduction related to the dramatic decrease of algae was manifested by landholders.

Turbitidity

The turbidity values in the stored water in the AWR during the experimental period were on average 50 and 5 Nefelometric Turbidity Units (NTUs) for the uncovered and the covered conditions, respectively. The cover prevents wind-borne dust and debris entrance to the AWR and limits algae growth.

Economic assessment

Monthly water balance

To determine the amount of water saved by reducing evaporation and the water saved by reducing filter cleaning requirements, the monthly water balance in the covered and uncovered AWR were established for a usual farming approach in the SRB. The following assumptions were established:

— The AWR is initially full (11,920 m^3).

— The AWR is refilled when 1/3 of the AWR capacity is reached.

— The cover is 84% and 90% effective in reducing evaporation and filter cleaning requirements, respectively.

— Filter cleaning requirements are 0 and 3% of the outflow from the AWR for irrigation purposes.

— Precipitation data are the mean monthly values in the basin, and AWR evaporation corresponds to annual Class-A pan values of 1,600, 1,800 and 2,000 mm year^{-1}.

— The AWR supplies 4 ha of irrigated land, where crop water requirements are 7,200 m^3 ha^{-1}, which are uniformly distributed throughout the year.

The simulation of several farm configurations (crops and land surface supplied from the AWR) under the same meteorological conditions (rainfall and evaporative demand) indicated that the crop water requirements and the surface area of irrigated land supplied by the AWR had little influence (1-2%) on the total amount of conserved water, as long as the AWR contains water throughout the year. The water saved by reducing filter cleaning requirements is small in comparison with the water saved by reducing evaporation. Hence we decided to maintain the assumptions of 4 ha of irrigated land with uniform water requirements of 7,200 mm year^{-1} ha^{-1}.

Viability of SSCCs under different scenarios

Figures 8a, 8b and 8c present the estimated NPV and IRR for the three levels of evaporation (1,600, 1,800 and 2,000 mm year^{-1} respectively) accounting for the economic value of saved water (ranging from €0.1 to 5 m^{-3}) and two levels of filter cleaning requirements (0 and 3% of the water for irrigation).

Water values higher than €0.5 m^{-3} were necessary to obtain a positive NPV in any situation. According to these results, the installation of the cover is not economically viable when the conserved water is valued at the current prices of water in the basin (€0.15 m^{-3} for surface water, €0.30 m^{-3} for groundwater and €0.50 m^{-3} for desalinized sea water).

For the most frequent case, which is a surface water supply and a filter cleaning requirement of 3%, the IRR is –6.52%, –5.80% and –5.15% for the evaporation levels of 1,600, 1,800 and 2,000 mm year^{-1} respectively. However, for the most favourable case, desalinized sea water supply and no filter cleaning requirements, the respective IRRs are 1.73%, 2.84% and 3.87% for the evaporation levels of 1,600, 1,800 and 2,000 mm year^{-1}.

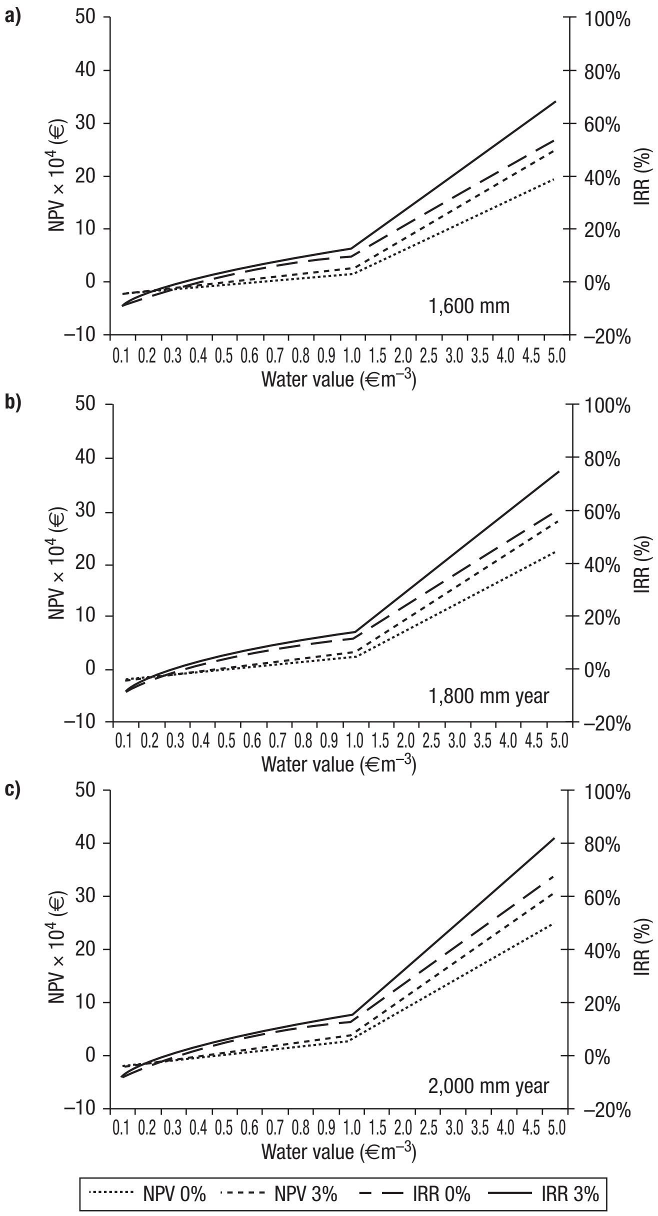

Figure 8. Net present value (NPV) and internal return rate (IRR) for three levels of Class-A evaporation rate: a) 1,600 mm year^{-1}, b) 1,800 mm year^{-1} and c) 2,000 mm year^{-1}. Filter cleaning requirements are 0 and 3%. Water values range from €0.1 to 5 m^{-3}.

Even for these favourable cases, the NPV reaches negative values that make the investment not economically viable.

The installation of the SSCC can be economically viable if water availability is the limiting factor in crop production, which is often the case in the SRB, and the saved water can be valued at the crop net margin. Table 3 provides the net margin per m^3 water for common crops in the Basin (Segura *et al*., 2006).

Table 3. Net margin per m^3 of irrigation water for most usual crops in the Segura River Basin (Segura *et al.,* 2006)

Crop	Number of evaluated	Average net margin (€ m^{-3})
Tomato (greenhouse)	5	6.20
Pepper (greenhouse)	5	4.00
Lettuce	9	1.30
Broccoli	4	0.55
Almond tree	4	2.00
Orange tree	4	1.80
Peach tree	11	1.95

For protected crops (*e.g.* pepper), whose net margin is €4.0 m^{-3}, the NPV is €215,600 and the IRR is 59.72% for an evaporation level of 1,800 mm year^{-1}. Under the same evaporation assumption, for orchards such as almond, orange or peach trees whose net margin is around €2 m^3, the NPV is €92,400 and the IRR is 27.71%. Finally, considering open-field horticultural crops, whose net margin is about €1 m^{-3}, the NPV is €30,800 and the IRR is 14.10%.

The economic viability of SSCCs investments grows when the water quality is poor and more water is required for filter cleaning. However, this effect is small; when filter cleaning requirements increase from 0 to 3% the IRR values increase on average less than 6% for the considered scenarios. On the other hand, the importance of the filtration requirements increases with water value: the slope of the NPV and IRR lines is higher for increasing water values.

Therefore the increase in the economic indicators results substantial and justifies the installation of SSCCs when water availability is the limiting factor to crop production, *i.e.* when the water is valued at the net margin of the crops.

Conclusions

Evaporation losses from AWRs can be very important in arid and semiarid climates. SSCCs can mitigate these important evaporation losses and save water for irrigation purposes.

An 84% evaporation reduction has been achieved in this study. This effect can be mainly ascribed to the high protection from incident solar radiation and wind speed provided by the cover. The energy and mass balances at the water surface are modified by the presence of the cover. Marked reductions in evaporation driving force and net radiation were observed. These reductions were particularly pronounced during the hot season. Besides evaporation reduction, conservation was enhanced by the high permeability of the cover, permitting the storage of 90% of rainfall.

The installation of the cover produced relevant effects on the quality of the stored water, which are particularly beneficial for drip irrigation systems. Algae growth was minimized and the deposition of dust and debris was prevented, thus reducing filtering requirements. The balance between rainfall and evaporation loss was positive and therefore the salinity of the stored water decreased.

From an economic point of view, the decision to install a SSCC will mostly depend on the value of water for the landowner in terms of the cost of purchasing water (regular water supply) or the profit from increased crop production (scarce water supply). On the other hand, the water conserved by reduced filter cleaning showed small positive impacts on NPV and IRR.

In summary, the technical viability of installing SSCCs on AWR has been demonstrated. The economic assessment indicated that SSCCs can be economically feasible when water availability is the limiting factor in crop production and the saved water is valued at the crop net margin, which is commonly the case of the Segura River Basin.

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