Spanish Journal of Agricultural Research (2006) 4(4), 280-288

Effect of black polyethylene shade covers on the evaporation rate of agricultural reservoirs

V. Martínez Álvarez*, A. Baille, J. M. Molina Martínez and M. M. González-Real

Department of Agricultural Engineering. Polytechnic University of Cartagena. P.º Alfonso XIII, 48. 30203 Cartagena (Murcia). Spain

Abstract

The potential use of shade covers to reduce evaporation from agricultural reservoirs motivated this study on the effect of black polyethylene shade on the evaporation rate from a small water body (Class-A pan) and of its driving variables. Evaporation was measured hourly in two pans during the summer in Cartagena (Spain), along with the measurements of air temperature and humidity, water temperature, solar radiation and wind speed. The first pan was uncovered whereas the second pan was covered with black polyethylene shade as either a single or double-layer. The main factors influencing reduced evaporation (mass transfer coefficient and surface-to-air vapour pressure deficit) were analyzed, focusing on the changes in the uncovered pan. In the shaded pan there was a decrease in daily evaporation of 75 and 83% for single and double-layer shade respectively. Condensation on the shade was considerable and was 14 and 21% of the daily evaporation losses for the single and double-layer shade respectively. It was concluded that (i) black polyethylene shade appears to be an efficient way to reduce evaporative loss from agricultural reservoirs, and (ii) an economic analysis of their implementation under the current scarce water supply, for agriculture, in southern Spain justified their use.

Additional key words: class-A pan, condensation, economic viability, farm dams, mass transfer coefficient, scale effect.

Resumen

Efectos de las coberturas de sombreo de polietileno negro sobre la evaporación de pequeños embalses agrícolas

La posibilidad de emplear coberturas de sombreo para reducir la evaporación en pequeños embalses de uso agrícola motivó el análisis de la incidencia de mallas de polietileno negro, tanto en la tasa de evaporación como en las variables microclimáticas implicadas, sobre un tanque evaporímetro Clase A. Durante el verano de 2003 se realizaron medidas de evaporación horaria en dos tanques evaporímetros localizados en Cartagena (España), así como de la temperatura y humedad del aire, la temperatura del agua, la radiación solar y la velocidad del viento. El primer tanque fue cubierto con mallas negras de polietileno, empleando dos configuraciones (simple y doble malla), mientras que el segundo permaneció descubierto durante la experimentación. Se analizaron los principales factores implicados en el proceso de evaporación (coeficiente de transferencia de masa y déficit de presión de vapor entre la superficie de agua y el aire), con especial incidencia en los cambios producidos respecto al tanque descubierto. Los resultados muestran una disminución de la tasa de evaporación diaria del 75 y 83% para las coberturas de simple y doble malla respectivamente. Se observó un importante efecto de recuperación de agua por condensación, que alcanzó el 14 y 21% de las pérdidas diarias por evaporación para las configuraciones de simple y doble malla respectivamente. Las conclusiones del estudio indican que: (i) las coberturas de sombreo de malla negra de polietileno suponen una solución eficiente para reducir las pérdidas por evaporación en embalses de uso agrícolas, (ii) el análisis económico de su implementación en embalses de riego del sureste español justifica su viabilidad bajo la actual coyuntura de escasez de recursos hídricos.

Palabras clave adicionales: balsas de riego, coeficiente de transferencia de masa, condensación, efectos de escala, tanque clase-A, viabilidad económica.

* Corresponding author: victoriano.martinez@upct.es
Received: 19-01-06; Accepted: 19-09-06.

All authors are members of the SEA.

Introduction

Due to the current water shortage in semi-arid Mediterranean regions, like south and south-east Spain, it is necessary to increase agricultural water management efficiency by modernising irrigation systems and developing new water saving technologies (Pereira *et al.*, 2002; Ortega *et al.*, 2005). In regions where irrigation water is not continuously available throughout the year, small dams are commonly used by both farmers and water associations.

Water losses by evaporation from farm dams may have an impact on farm revenues (Hudson, 1987; Mugabe *et al.*, 2003). In regions with high solar radiation and air vapour pressure deficits, evaporative losses are a substantial amount of total stored water leading to low overall water use storage efficiency. In southern Spain potential evaporation is 1,600 to 2,000 mm year^{-1}. Bengoechea *et al*. (1991) estimated evaporative loss from farm dams was about 15% of the total water supplied to the irrigated area. Any savings gained by reducing these losses could significantly improve overall agricultural water use efficiency of the region.

Efforts to limit evaporation from reservoirs are not new. Several techniques were implemented and tested during recent decades (Brown, 1988), however, most of them were not efficient in the long term, or were not technologically or economically viable in reducing evaporation from dams. Among these techniques were the application of floating synthetic mono-layers on the water surface (Barnes, 1986), mixing systems to reduce the thermal stratification of the water (Koberg and Ford, 1965), floating bodies to reduce mass and energy exchanges at the inter-phase water to atmosphere (Laing, 1991; Daigo and Phaovattana, 1999), the application of different colours to modifying the water albedo (Cooley, 1983) and the use of trees as windbreaks (Hipsey and Sivapalan, 2003; Hipsey *et al*., 2004). Among the most efficient solutions, the use of shade (films supported by a metal frame) significantly reduces evaporation (Crow and Manges, 1967; Cluff, 1975). However, the sensitivity of these structures to the wind limits their agricultural application. However, the problem could be overcome by covering the water with porous shade screens (Finn and Barnes, 2002; DNRM, 2003).

In southern Spain, some farmers are aware of the benefits of reducing water loss from their dams and have isolated the water surface from the outside environment. A common system is the installation of porous shade on a light structure made of a double reticular frame (0.5 × 0.5 m) of metal or plastic cables. The structure is fixed and tied to concrete walls or metal post foundations by means of wires. If the size of the dam exceeds 60 m breadth, intermediate posts are used. The frame sandwiches the shade, which is generally a single or double layer of black polyethylene shade cloth.

The general use of this kind of structure requires more information on their technical efficiency and economic viability under the conditions of southern Spanish farming. The porosity of the covering material to air and rain should match the conditions of structural stability and resistance of the walls and/or foundation posts. Little attention has been paid to this issue and results of only a few studies are available (Cluff, 1975; Finn and Barnes, 2002; DNRM, 2003). A rigorous evaluation of the microclimatic variation and the reduction of evaporation from free surfaces by the use of such shade covers are required. The characteristics of the shade cloth (optical properties, porosity and roughness) affect the processes of energy and mass exchanges at the water surface in a complex way. Radiative and aerodynamic exchanges from the water surface to the outside air are substantially modified by the presence of the shade, and a specific microclimate is created in the air volume between the water and screen surfaces. Therefore knowledge of the effect of a given screen type on the energy and mass exchange at the water surface is needed to determine the optimum screen type and characteristics.

The aim of this study was to characterise the effect of black polyethylene shade screens on the evaporation rate from small bodies of water and on its driving variables. To facilitate measurement of the evaporation rate and the microclimate and to implement the shade screens measurements were made on a small scale water surface (Class-A evaporation pan). This choice was also justified because there is a large body of knowledge on the physical behaviour of open pan evaporation. This gives a valuable basis for the interpretation of the results and their application to farm dams (e.g. Linacre, 1994; Jacobs *et al.*, 1998; Molina *et al.*, 2006). From the small scale evaporation analysis, the application of the results to full scale dams was investigated through (i) extrapolation of the overall evaporation reduction coefficients from pans to farm dams and (ii) an evaluation of the economic viability of the system under the scarce water situation of southern Spain.

Material and Methods

Experimental facilities

The experiments were carried out at the Polytechnic University of Cartagena Experimental Station in southern Spain (37°35' N, 0°59' W), which has a semiarid climate. Two Class-A pans located in an uncultivated field were used following the recommendations of the World Meteorological Organization (WMO, 2006). The tanks walls and bottom were thermally isolated from the environment by a layer of glass wool with one air filled external sub-layer (10 cm thick on the bottom and 5 cm thick on the walls) to minimize energy exchange between the metallic pan surface and the external environment. The metal structure supporting the screens (3 m wide and 0.30 m above the water surface) was made of an open light metal frame.

Evaporation measurements

Measurement of the pan evaporation rate (*E)* was performed on both the covered and the uncovered pan. A system of communicating vessels was used, by which the pan was connected, through a flexible pipe, to an auxiliary reservoir mounted on an electronic balance (BP 4100, SARTORIUS, Germany, range 0-4,000 g, resolution ± 0.1 g), allowing continuous measurement of the reservoir weight. An automated system (Molina *et al.*, 2003) replenished the tanks when *E* reached its minimum value and to maintain the water level between the minimum and maximum values recommended by WMO (2006).

Microclimate measurement

Only the pan on which the screens were tested was fully equipped and monitored for microclimatic variables. Water temperature was measured at the surface (T_s) and near the bottom of the pan at a depth of 24 cm (T_b) with two cylindrical sensors (RTD Pt100, Desin Instruments, Spain) with two stainless steel sheaths (15 and 30 cm long, respectively). The sensors measuring the microclimate (air temperature, T_a; relative humidity, *RH*; solar global radiation, *S*; and wind speed, *V*) were installed on a mast and located below the screen (at 15 cm above the water surface) and above it, at 200 cm above the ground. The values of the different climate variables (*X*) measured at 15 cm and at 200 cm were recorded as X_{15} and X_{200} respectively. The air temperature (Pt-l00 sensor) and relative humidity (HUMICAP 180) sensors were located in a fan-ventilated shelter (HMP45A, Vaisala, Finland). Wind velocity below the screen, V_{15}, was measured by a hot wire anemometer (TSI-8455, TSI, USA; range 0-20 m s^{-1}; resolution ± 0.1 m s^{-1}). Wind speed at 2 m (V_{200}) was measured with a cup anemometer (A100R, Vector Instruments, Spain, range 0.2-75 m s^{-1}, resolution ± 0.2 m s^{-1}). Incident and transmitted solar radiation (*S* and S_t, respectively) were measured using two SI-photocell sensors (SP1110, Skie Instruments, Wales). An albedometer (SP1110-inverted), located above the screens, was used to measure reflected solar radiation (S_r). Solar radiation absorbed by the shade cloth (S_a) was obtained from $S_a = S - S_t - S_r$.

The sensor signals and those of the electronic balances were sampled at 10 s intervals by an acquisition card, averaged every 30 min and stored on a PC, located inside a small insulated shelter, 20 m from the pans.

The shade covers

The top and sides of the metal structure which supported the screens were covered in porous black polyethylene (BPE) shading cloth with two different configurations*:* a single-layer (1-BPE) and a double-layer (2-BPE). These were chosen because they are the most common configurations that farmers use on their farm dams. Prior to taking the measurements, values of the components of perceived colour, following CIE methodology (AENOR, 1983), were determined for the screen, using a colorimeter (CR-300, Minolta, USA).

The CIE methodology was proposed by the *Commission Internationale de l'Eclairage* (McLaren, 1976) for standard values that are used worldwide to measure colour.

Values used in the CIE method are called «brightness», *a* and *b*. «Brightness» represents the difference between light (100) and dark (0), where the parameter *a* represents the difference between green (–*a*) and red (+*a*) and the parameter *b* represents the difference between yellow (+*b*) and blue (–*b*). Using this system for the BPE screens, *a* = –0.05, *b* = 0.28 and brightness was 22.3%.

Experimental protocol

The experiment was conducted in May and June, 2003. For each configuration, continuous measurements runs of 10-d period were taken on the fully monitored pan. Prior to and after measurement with shading, several periods of 3-4-d were used to take measurements without shade. The other pan, left uncovered all the time, gave values corresponding to open pan evaporation (E_{OP}), which was used as reference for calculating the evaporation reduction induced by the different levels of shade.

To compare the effects on the microclimate of both configurations (1-BPE and 2-BPE), only «sunny days» (those without interactions of cloud in the daily trend of *S*) were selected for each 10-d trial corresponding to a given shade and from several data sets corresponding to the open pan. The average value, over these days, of the climatic variables and the microclimate variables was calculated for each hour of the day. This yielded an «average day» for the two shade treatments and for the open pan.

Determination of the mass transfer coefficient

The pan evaporation rate (E, kg m^{-2} s^{-1}), was considered to be proportional to the vapour pressure gradient between the water surface and the air at its vicinity (Δe_s) through a convective coefficient for water vapour transfer (h_v):

$$\lambda E = \frac{\rho C_p h_v \Delta e_s}{\gamma} \qquad [1]$$

where λ is the latent heat of water vaporization (J kg^{-1}), ρ is the air density (kg m^{-3}), C_p is heat capacity of the air (J kg^{-1} K^{-1}) and γ the psychrometric constant (kPa K^{-1}). The value Δe_s (kPa) stands for the gradient e_s–e_{15}, where e_s is the saturated vapour pressure at the surface temperature (T_s) and e_{15} is the actual vapour pressure derived from the measurements of T_a and *RH* at 15 cm. The value of h_v (m s^{-1}) was calculated from Eq. [1] at an hourly scale, using measured values of *E* and Δe_s. In the following, h_v is given in mm s^{-1}.

Values of h_v were considered to be linearly dependent on wind speed, *V*, at the reference height over the water surface (Xu and Singh, 1998). Therefore, the influence of wind speed on h_v was analyzed assuming the following linear relationship, in which *V* stands for the velocity measured at 2 m (V_{200}):

$$h_v = a V + b \qquad [2]$$

Equations [1] and [2] indicated that a reduction in the evaporation rate can be analyzed through the influence of the shade on (i) the radiative balance at the water surface (and hence, on T_s and on the gradient Δe_s [Eq. 1]) and (ii) a reduction of the aerodynamic term (h_v) due to lower values of air velocity and changes in the turbulence intensity induced by the shade at the water surface. These two effects are not independent, as changes in h_v due to changes in wind speed also affect convective fluxes (sensible, H_s, and latent, *E*), and consequently, the water and screen surface temperatures and their respective energy balance.

Results

Effects on the solar radiation incoming at the water surface

Average values during daylight of the fraction of solar radiation reflected ρ = (S_r/S), transmitted τ = (S_t/S), and absorbed α= (S_a/S) by the two shade configurations were calculated. The data showed that 1-BPE and 2-BPE shade transmitted a very low percentage of solar radiation (τ = 6.4% [*SD* = 0.6%] and τ = 0.8% [*SD* = 0.6%] respectively) due to its high absorptive capability (α = 78.6% [*SD* = 6.2%] and α = 86.7% [*SD* = 3.4%] respectively). The use of a double layer of shade cloth changed the effect of the incoming solar radiation slightly by increasing α by 8% and reducing τ by 6%.

Effects on wind speed near the water surface

There was a quasi linear relationship between V_{15} and V_{200}. The linear regression $V_{15} = a V_{200} + b$, supplied high values of r^2 (> 0.90) for the two shade types as well as for the open pan (Fig. 1). The average reduction in wind velocity compared to that at 2 m was about 58% for OP, 91% for 1-BPE and 94% for 2-BPE. The double layered shade gave a slightly higher reduction in wind speed than a single layer.

Effect on the mass transfer coefficient

The values derived for h_v showed a linear dependence on the wind speed at 2 m. The linear regressions for 1-BPE and 2-BPE are compared, in Fig. 2, to that

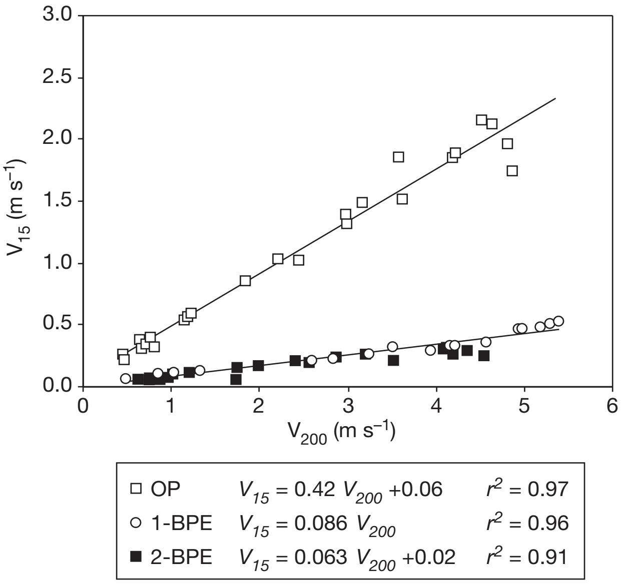

Figure 1. The relationship between V_{15} and V_{200} for open pan (OP), single layer of black polyethylene (1-BPE) shade and double layer of black polyethylene (2-BPE) shade.

for the open pan. The 2-BPE cover was the most effective in reducing h_v. The average reduction of h_v for a wind speed of about 3 m s^{-1} was about 42% for 1-BPE, and 60% for 2-BPE.

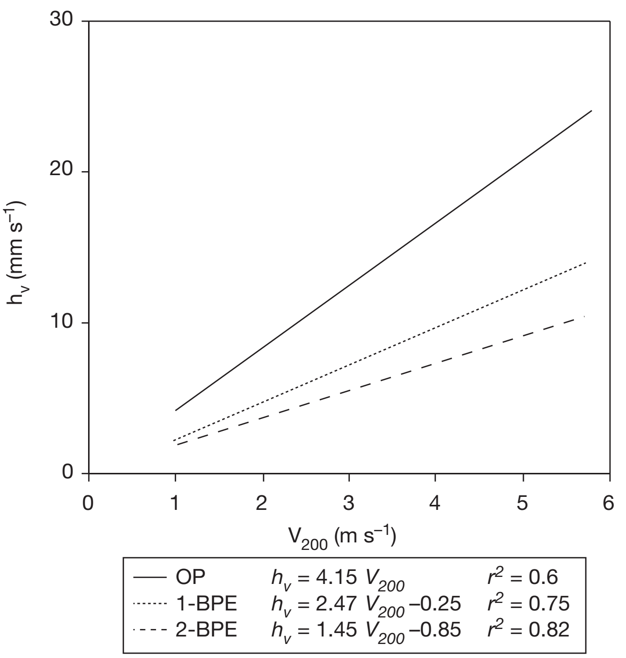

Figure 2. The relationship between h_v and the speed measured at 2 m for open pan (OP), single layer of black polyethylene (1-BPE) shade and double layer of black polyethylene (2-BPE) shade.

Effect on vapour pressure deficit

Modifications of values of T_s, T_{a15} and HR_{15} induced by the shade changed the vapour pressure deficit, Δe_s. To compare the effect on Δe_s, the average value over the «sunny days» of the climatic variables and those of T_s and e_s were calculated for each hour of the day, yielding the «average day» for the two shade types and for the open pan (Fig. 3).

The daily trend of Δe_s showed significant differences between shaded pans and the open pan. The 1-BPE and 2-BPE shades strongly reduced Δe_s (about 64% and 66% respectively for the daily average of Δe_s). The period of maximum reduction in Δe_s was from 12:00 to 20:00 h solar time, when evaporation was at its highest rate during the day.

Effect on the dynamics of surface temperature

Shading the pan affected the thermal behaviour characterizing the open pan, as shown in the water temperature gradient, T_s-T_b (Fig. 4).

Without shade, and for a large range of weather conditions, there was no evidence of thermal strati-

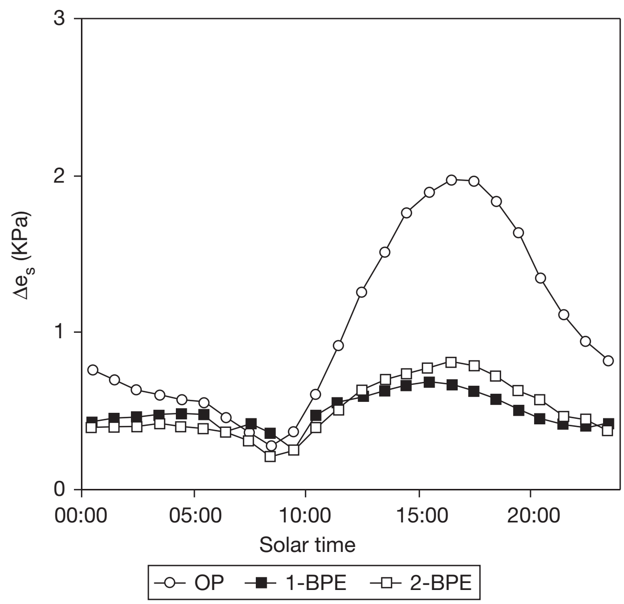

Figure 3. The daily pattern of the surface-to-air vapour pressure gradient, Δe_s, for open pan (OP), single layer of black polyethylene (1-BPE) shade and a double layer of black polyethylene (2-BPE) shade. Data are hourly values averaged over a period of several sunny days (average day).

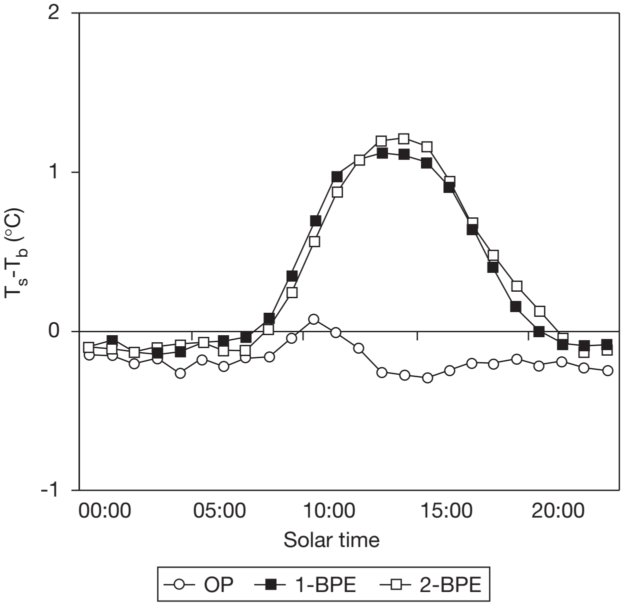

Figure 4. Daily variation in temperature gradient in the pan, T_s - T_b, for open pan (OP), a single black polyethylene shade layer (1-BPE) and double black polyethylene (2-BPE) shade layer. Data are hourly values averaged over a period of several sunny days (average day).

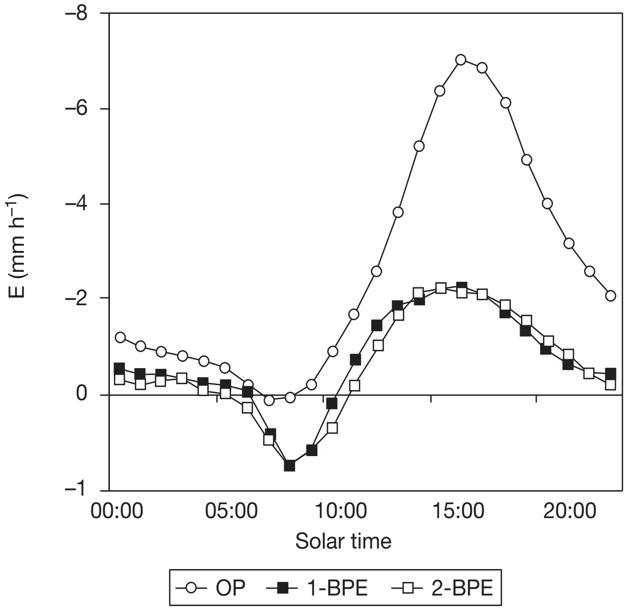

Figure 5. Daily variation in pan evaporation rate, E, for open pan (OP), the single layer of black polyethylene (1-BPE) shade and a double layer of black polyethylene (2-BPE) shade. Negative values correspond to condensation. Data are hourly values averaged over a period of several sunny days (average day).

fication in the open pan, which can be considered an isotherm. Such an isothermal behaviour was not seen in shaded pans, where there was a clear stratification during the day period (about 1°C), which disappeared with the onset of night. During the night, the water in the pan remained isotherm under the shade. No clear differences were observed between the 1-BPE and 2-BPE screens in T_s and T_b.

Effect on evaporation and condensation rates

The two BPE shades reduced E during the whole 24 h (Fig. 5). The reduction can be ascribed to lower values of h_v and Δe_s under the shade (Figs. 2 and 3). The maximum evaporation value was about 0.7 mm h^{-1} in the open pan. However, it only reached 0.2 mm h^{-1} under shade. The shade slightly affected the time of peak evaporation which was near 15:00 h solar time in the open pan and a little earlier (1 h) in the shaded pans.

Condensation, which corresponds to negative E values in Fig. 5, was strongly enhanced in shaded pans and had a peak value of about –0.17 mm h^{-1}. It was insignificant in the open pan. Condensation occurred for about 4 to 5 h, from 6:00 h until 10:00 h solar time, corresponding to the period of lower Δe_s values (Fig. 3).

At a daily level, the fraction of evaporation reduction due to condensation was 14.5 and 22.1% for the 1-BPE and 2-BPE shade respectively, compared to 1% for the open pan. The daily condensation rate in shaded pans was about 0.7 mm day^{-1}. It was less than 0.1 mm day^{-1} in the open pan. The high rate of condensation observed under the shade cloth covers may have been due to a high value of radiative losses inherent to a high emissivity coefficient of the shade screens. The low screen temperature values, at the end of the night with respect to the surrounding air temperature probably favoured condensation at the shade surface.

For practical purposes, independently of the relative importance of the processes of evaporation reduction and condensation enhancement, the parameter of interest is the «overall» evaporation reduction factor (f_R) which integrates all the previously described processes, and can be defined as:

$$f_R = 1 - E_S / E_{OP} \quad [3]$$

where E_{OP} (mm day^{-1}) is the daily evaporation of the open pan, and E_S (mm day^{-1}) the corresponding value for a given shade cover. This parameter was calculated for the two shade screens from the daily values of E_{OP}

and E_S, obtained on the same day, from the shaded and uncovered pans. The values of $f_{R,}$ averaged over the measurement period, were 0.751 (SD = 0.058) for 1-BPE and 0.835 (SD = 0.023) for 2-BPE.

Discussion

Effect on the evaporation rate and its driving variables

This study gave an insight into the mechanisms involved in the reduction of E induced by the use of black polyethylene shade screens placed over a freely evaporating surface. Both 1-BPE and 2-BPE shade screens markedly reduced the convective coefficient for water vapour transfer, h_v, and strongly decreased the surface-to-air vapour deficit, Δe_{15}, and consequently E. As expected, the highest reduction was achieved with the 2-BPE screen, which gave (i) the greatest reduction in h_v and τ, and (ii) better conditions for the condensation process.

The high overall evaporation reduction factor, f_R, obtained for the single and double layered shades, can be explained by (i) the reduction of h_v (aerodynamic effect, Fig. 2), and (ii) the reduction of τ (shade effect), which in turn strongly decreased Δe_s with respect to the open pan values (Fig. 3). Hence, both the aerodynamic and shade effects were substantial. Considering Eq. [1], the impact of 1-BPE on Δe_s (a reduction of 64% in the daily value of Δe_s), added to the aerodynamic effect (a reduction of 42% in h_v), would lead to a total reduction of E of about 79% $[1-(0.36 \cdot 0.58)]$ compared with the open pan. For 2-BPE, daily values of Δe_s and h_v were reduced by 66 and 60% respectively, giving a total reduction of E of about 86% $[1-(0.34 \cdot 0.40)]$. For both shade configurations, these values agreed fairly well with values of f_R derived from the experimental data (75.1 and 83.5% for 1-BPE and 2-BPE respectively). Thus, there was a coherent relationship between the effect of shade covers on E and on its driving variables.

The observed condensation and water recovery represented a significant fraction of the measured evaporation. It is probable that most of the condensation, measured by the scale originated from the water condensed on and between the screens, which later dropped into the pan. Two aspects need to be distinguished in the analysis of the condensation: (i) the role of the shade screen as a water condenser and (ii) its ability to transfer condensed water to the pan (dripped condensation on the water surface). With regard to the first, related to the physics of condensation, the long-wave optical properties of the shade are of primary importance. A high emissivity will favour condensation (this seemed to be the case of the PE materials). With regards to the second aspect (collection of dripped condensation), the dimension of the reticular pores should be large enough to allowing water drops to fall onto the pan surface. Very small pores would retain condensed water, due to adhesion and capillarity forces between the water and the shade screen, leading to evaporation of this water at sunrise. A supplemental factor which can influence collection of dripped condensation is the hygroscopic properties of the shade plastic material, which may favour drop-like or film-like condensation (Jaffrin and Morisot, 1994).

To summarize, selection of the most efficient shade material, as shows this paper, must combine high performance in the basic function of reducing evaporation during the day (radiative and aerodynamic properties), with high efficiency of condensation and recovery during the night. The shade screen materials tested in this study appear to fulfil these criteria.

Thermal behaviour of the pan

The isothermal behaviour of the open pan agreed with previous reports (Losordo and Piedrahita, 1991; Jacobs *et al.*, 1998; Molina *et al.*, 2006), supporting the hypothesis that the Class-A pan behaves as a perfectly stirred tank. During the day, wind speed and turbulence at the pan surface were the main cause of mixing. At night, when very low winds frequently occur, natural convection, due to the radiative cooling of the water surface, appears to be sufficient to homogenize the temperature field.

Shading a pan affects isothermal behaviour. A clear stratification process prevailed during the diurnal period that can be mainly ascribed to a reduced h_v induced by the shade screens near the water surface, thus diminishing mixing intensity. The reduction of h_v was mainly due to a reduction of V induced by the shade screens that reduced turbulent mixing and favoured thermal stratification during the day.

Extrapolation to farm dams

Extrapolation of these results to real farm dams can be done by considering the eventual effects due to the size of the water body (and then of the shade size) on the values of the reduction factor, f_r, obtained for the shade material tested in this study. The effect of the screen optical properties will be identical, irrespective of the dimensions of the water body, as these properties do not change with reservoir size. Therefore, the reduction in the surface-to air vapour water gradient, which is mainly due to the decrease in net radiation, and the condensation process, which depends on the long wave optical properties of the screen, will not be affected by reservoir size or the shade (Tanny *et al.*, 2003).

How reservoir size reservoir would reduce wind velocity near the water surface (Fig. 1) and hence, the water vapour transfer coefficient (Fig. 2) determined in this study, is more difficult to evaluate. Wind velocity near the water surface is strongly attenuated and is less than 10% of the wind velocity at 2 m (Fig. 1). Very few experimental studies are available that deal with the reduction of wind velocity under large shaded structures. Tanny and Cohen (2003) characterized the aerodynamic properties of agricultural screens aimed at protecting crops. They measured a reduction of 40% of wind speed under a shade net covering a citrus orchard. However, the sides of the structure were open, allowing the wind to enter, and the experimental plot was small (9 m fetch). More comparable to the case of shaded dams is the study of Tanny *et al.* (2003), who dealt with wind velocity under a commercial flat-top screen house 110 m long by 60 m wide, whose roof and sidewalls were covered with a single screen made of round monofilament threads. Their measurements indicated that, for an outside velocity of about 2 m s^{-1}, the internal velocity was about 0.25 to 0.30 m s^{-1}, a reduction of the same order of magnitude as that found for the single BPE shade screen in this study. It appears therefore that the magnitude of wind speed reduction found in shaded pans was not far from the wind velocity that would prevail in a real farm dam.

In conclusion, the reduced evaporation under the shade covers was driven by the variation in Δe_s and h_v, which depends on the optical and aerodynamic properties of the shade material, and is probably little affected by scale. Therefore, f_R values in the shaded pans can be extrapolated to real farm dams, taking into account that other secondary process, like mixing or thermal inertia that could be affected for the shade cover, can slightly modify f_R over time.

Economic viability

The implementation of shade covers over farm dams would require a more expensive and resistant structure than that used for the Class-A pan. A shade only involving capital costs as operating costs of maintenance, repair and labour would only occur under extraordinary circumstances. Currently, commercial firms estimate the cost of a large shade structure at 7 € m^{-2}, including perimeter works to anchor the structure. They guarantee a life of 10 years, and consider that 15 years is a reasonable expected life span for the entire structure.

The benefit of the shades is a reduction in evaporation, which could amount to about 1.5 m^3 m^{-2} $year^{-1}$ (with an evaporation rate of 1,800 mm $year^{-1}$ and an f_R of 83.5% [2-BPE]). The economic value of the water saved differs with their origin. Representative water prices (WP) in southern Spain are 0.15 € m^{-3} for surface water, 0.30 € m^{-3} for groundwater and 0.50 € m^{-3} for desalinated sea water.

To evaluate the potential of erecting shading covers, a simple comparison of (i) the equivalent annual cost (EAC) of the initial cost, based on a 15 year useful life, and an interest rate of 5%, and (ii) the annual economic benefit (AEB = 1.5 m^3 m^{-2} $year^{-1}$ WP € m^{-3}) for each water source was applied. The results indicated that the investment would only be economic for the replacement of desalinated sea water (EAC = 0.672 *vs.* AEB = 0.750 € m^{-2} $year^{-1}$).

However, saved water may lead to an increase in the cultivated area. Therefore, the economic analysis must evaluate the saved water taking into account the net benefit (€ m^{-3}) of its use, which is over 1 € m^{-3} for most local irrigated crops (greenhouse crops, vegetables, ornamentals, fruit trees). Under this hypothesis, the AEB of shaded farm dams would be more than 1.5 € m^{-3} $year^{-1}$, i.e. double the EAC (0.67 € m^{-3} $year^{-1}$). This result of the cost/benefit analysis indicate that, under the prevailing conditions of water scarcity in southern Spain, shade covers might be a realistic option for increasing agricultural water use efficiency. Further, the analysis did not take into account other advantages associated with the use of shade, such as a decrease in algal growth, decreasing the need for filtering for drip irrigation and the increased useful life of the farm dam waterproof membranes.

With regard to the selection of a single or double layered shade cover; the use of the 2-BPE screen increases cost by about 5% compared with a single layer, whereas the decrease in evaporation was 8.4%. These figures suggest that it is advisable for farmers and water associations to use two layer shade screens in the climatic and water pricing conditions of southern Spain.

Acknowledgements

The authors acknowledge the *Fundación Séneca* (Murcia, Spain) for their financial support of this study through grant 02978/PI/05 «Evaporación de agua en embalses de regulación de riego: modelización del proceso y estudio de la viabilidad técnica y económica de su reducción mediante técnicas de sombreo».

References

AENOR, 1983. UNE 72031/83 Método CIELAB. Asociación Española de Normalización y Certificación, Madrid. 16 pp.

BARNES G.T., 1986. The effects of monolayers on the evaporation of liquids. Adv Colloid Interface Sci 25, 189-200.

BENGOECHEA J.M., PÉREZ J., PÉREZ-PARRA J., LÓPEZ J.G., 1991. Evaluación de las pérdidas de agua de Riego en el Campo de Dalías, Almería. III Symposium sobre el agua en Andalucía. Córdoba, Spain.

BROWN J.A.H., 1988. The potential for reducing open water evaporation losses: a review. Hydrology and Water Resources Symposium. ANU, Canberra, Australia, pp. 108-115.

CLUFF C.B., 1975. Engineering aspects of water harvesting research at the University of Arizona. Proc Water Harvesting Symposium, Phoenix, Arizona, pp. 27-39.

COOLEY K.R., 1983. Evaporation reduction: summary of long-term tank studies. J Irrig Drain. E-ASCE 109, 89-98.

CROW F.R., MANGES H.L., 1967. Comparison of chemical and non-chemical techniques for suppressing evaporation from small reservoirs. T ASAE 10, 172-174.

DAIGO K., PHAOVATTANA V., 1999. Evaporation and percolation control in small farm ponds in Thailand. Jap Agr Res Quart 33, 47-56.

DNRM, 2003. Methods for reducing evaporation from storages used for urban water supplies. Final Report 41/12219/67346. Department of Natural Resources and Mines. Queensland, Australia. 19 pp.

FINN N., BARNES S., 2002. Evaporation trials for Gale Pacific. CSIRO Textile and Fibre Technology, 26 pp.

HIPSEY M.R., SIVAPALAN M., 2003. Parameterizing the effects of a wind shelter on evaporation from small water bodies. Water Resour Res 39, No. 12, 1339, doi: 10.1029/2002WR001784.

HIPSEY M.R., SIVAPALAN M., CLEMENT T.P., 2004. A numerical and field investigation of surface heat fluxes from small wind-sheltered waterbodies in semi-arid Western Australia. Environ Fluid Mech 4, 79-106.

HUDSON N.W., 1987. Soil and water conservation in semiarid regions. FAO Land and Water Conservation Service, Rome. 256 pp.

JACOBS A.F.G., HEUSINKVELD B.G., LUCASSEN D.C., 1998. Temperature variation in a class A evaporation pan. J Hydrol 206, 75-83.

JAFFRIN A., MORISOT A., 1994. Role of structure, dirt and condensation on the light transmission of greenhouse covers. Plasticulture 101, 33-44.

KOBERG G.E., FORD M.E., 1965. Elimination of thermal stratification in reservoirs and resulting benefits. United States Geological Survey, paper 1809-M.

LAING I.A.F., 1991. Evaporation reduction from water storages. Department of Agriculture, Western Australia. 39 pp.

LINACRE E.T., 1994. Estimating U.S. Class-A pan evaporation from few climatic data. Water Int 19, 5-14.

LOSORDO T.M., PIEDRAHÍTA R.H., 1991. Modelling temperature variation and thermal stratification in shallow aquaculture ponds. Ecol Model 54, 189-226.

McLAREN K.,1976. The development of the CIE 1976 (L*a*b*) uniform colour-space and colour-difference formula. J Soc Dyers Col 92, 338-341.

MOLINA J.M., MARTÍNEZ V., MARTÍN B., 2003. Automatización con control horario del llenado de tanques evaporímetros clase A. II Congreso Nacional de Agroingeniería, Córdoba, Spain. pp. 451-452.

MOLINA J.M., MARTÍNEZ V., GONZÁLEZ-REAL M.M., BAILLE A., 2006. A simulation model for predicting hourly pan evaporation from meteorological data. J Hydrol 318, 250-261.

MUGABE F.T., HODNETT M.G., SENZANJE A., 2003. Opportunities for increasing productive water use from dam water: a case study from semi-arid Zimbabwe. Agr Water Manage 62, 149-163.

ORTEGA J.F., DE JUAN J.A., TARJUELO J.M., 2005. Improving water management: The irrigation advisory service of Castilla-La Mancha (Spain). Agr Water Manage 77, 37-58.

PEREIRA L.S., OWEIS T., ZAIRI A., 2002. Irrigation management under water scarcity. Agr Water Manage 57, 175-203.

TANNY J., COHEN S., 2003. The effect of a small shade net on the properties of wind and selected boundary-layer parameters above and inside a citrus orchard. Biosyst Eng 84, 57-67.

TANNY J., COHEN S., TEITEL M., 2003. Screenhouse microclimate: an experimental study. Biosyst Eng 84, 331-341.

WMO, 2006. Guide to meteorological instruments and methods of observation. WMO No. 8, Secretariat of the World Meteorological Organization, Geneva, Switzerland. 569 pp.

XU C.Y., SINGH V.P., 1998. Dependence of evaporation on meteorological variables at different time-scales and intercomparison of estimation methods. Hydrol Process 12, 429-442.