The combined use of shade-cloth covers and monolayers to prevent evaporation in irrigation reservoirs

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Abstract

One of the most efficient techniques to prevent evaporation is suspended shade covers, reported to reduce evaporation up to 85%, although at considerable cost. Another option is the application of a chemical monolayer which creates a film over the water surface that can reduce evaporation, but performance of these is limited by environmental exposure. In this study, a detailed trial was conducted in southern Queensland (Australia) to assess the benefits of the combined use of monolayers and shade-cloth covers. Three experimental tanks were monitored to measure evaporation, water temperature profile and the meteorological factors driving evaporative demand. Tanks 1 and 2 were covered with a black polyethylene mesh; a monolayer was added to Tank 2; and Tank 3 was uncovered and used as a control. The comparison of Tanks 1 and 2 with Tank 3 provided the evaporation reduction factors. The differences between the reduction factors of Tanks 2 and 3 allowed assessment of the performance of the combination of the two evaporation-suppression methods.

Keywords: polyethylene meshes, storage efficiency, water management.

1. Introduction

The current worldwide population growth and increase of living standards have led to a strong competition for water resources. Only if water for agriculture is properly managed will there be sufficient water resources to produce food over the next 50 years (de Fraiture and Wichelns, 2010). The identification and control of water losses is an important aspect of good water management within irrigation schemes. One important water loss which is seldom prevented is evaporation from reservoirs. These losses are always undesirable and unrecoverable (Carter et al., 1999). Evaporation losses can represent an important percentage of the stored water, especially in arid and semiarid climates (Mugabe et al., 2003, Gallego-Elvira et al., 2010). In the semi-arid south-eastern Spain, Martínez-Alvarez et al. (2008) estimated that the evaporation water loss from agricultural reservoirs represents 8.3% of the irrigation water use on a regional scale. 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 highlight the urgent need to improve water management by developing new water-saving technologies, particularly in agriculture.

A wide variety of methods are available to mitigate evaporation from reservoirs. Physical structures such us floating (Daigo and Phaovattana, 1999) or suspended (Martinez-Alvarez et al., 2006) covers or windbreaks (Hipsey and Sivapalan, 2003) can be deployed to prevent evaporation. These structures minimize energy and mass exchanges between the water surface and the surrounding air and hence hinder the evaporation process. Chemical water-saving products are also available to prevent evaporation. Monolayers, like cetyl alcohol or stearyl alcohol, spread over the water surface to create a film that provides moderate evaporation reductions (10 - 40%) (Craig et al., 2005). Their limitation is that the monolayer can be negatively affected by dust particles, interactions with dam bacteria and product displacement by wind drag (Barnes, 2008). However, the material is applied to the surface only in periods when it is economically justified to do so (and only when there is water to protect).

Suspended shade-cloth covers have been pointed out as one of the most promising techniques for evaporation control (Craig et al., 2005; Martínez-Alvarez 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-Alvarez et al. (2010) reported an annual reduction close to 85% in the evaporation rate in an on-farm water reservoir (2400 m^2, 5m depth) covered with a double black polyethylene cloth in south-eastern Spain. However, the cost of such evaporation reduction (per megalitre saved) is relatively high and difficult to justify in Australian conditions when a storage may be empty for long periods.

In this study, a detailed trial was conducted to assess the benefits of the combined use of monolayers and shade-cloth covers. The main aim was to evaluate if the application of monolayer in water storages equipped with suspended covers increases the evaporation reduction factor; and a further potential advantage of the combination would be that the monolayer would still be effective at higher windspeeds, conditions in which an exposed monolayer would be destroyed. The performance of black polyethylene shade covers was also tested under the summer climate conditions of south-eastern Queensland and compared to previously reported results.

2. Materials and methods

2.1. Study site

The trial was conducted in the evaporation research facility of University of Southern Queensland (Toowoomba, Queensland, Australia). Three experimental tanks, 10 m diameter and 0.8 m depth, were monitored to measure evaporation rate, water temperature profile and evaporation driving meteorological factors. Tanks 1 and 2 were covered with a shade-cloth. A monolayer formulation was added to water surface of Tank 2; Tank 3 was left uncovered and used as a control.

2.2. Cover description

Tanks 1 and 2 were covered with a commercial shade-cover (product name: ATARSUN, manufacturer: ATARFIL) which is a double polyethylene porous cloth. Its main features are a very low transmission of solar radiation, high sheltering to wind and high permeability to rain. Martínez-Alvarez et al. (2010) tested the properties of this cover in south-eastern Spain and reported 99% reduction of solar radiation, 92% reduction of wind and 90% permeability to rainfall.

2.3. Monolayer

The monolayer formulation used in this study was octadecanol ($C_{18}H_{37}OH$) in suspension with water and the surfactant Brij 78 (50 mg octadecanol per mL). This chemical spontaneously self-spreads creating a film over water surface. It reduces evaporation through two mechanisms: increased surface resistance through the orderly packing of the molecules, labelled the 'condensed phase', and calming of the surface capillary waves which hinders disruption of the diffusion layer. Under laboratory conditions the formulation maintained a surface pressure of between 45 and 40 mN/m for at least 5 days. The formulated monolayer was applied to the surface of one of the ATARSUN covered tanks (Tank 2) two time during the trial at a rate of 0.28 mL/m^2 (equivalent to six times a monomolecular thickness), to ensure coverage of capillary waves and to maintain a surface pressure of above 35 mN/m (Barnes 2008). Surface pressure could not be monitored during the tank trial due to the presence of the covers. However, maintenance of the condensed monolayer film on the surface of Tank 2 was expected to increase the temperature of the water surface relative to the covered Tank 1, to which no monolayer was applied. The water temperature profile of Tanks 1 and 2 were monitored for evidence of the condensed monolayer increasing surface temperature.

2.4. Evaporation, water temperature and meteorological data

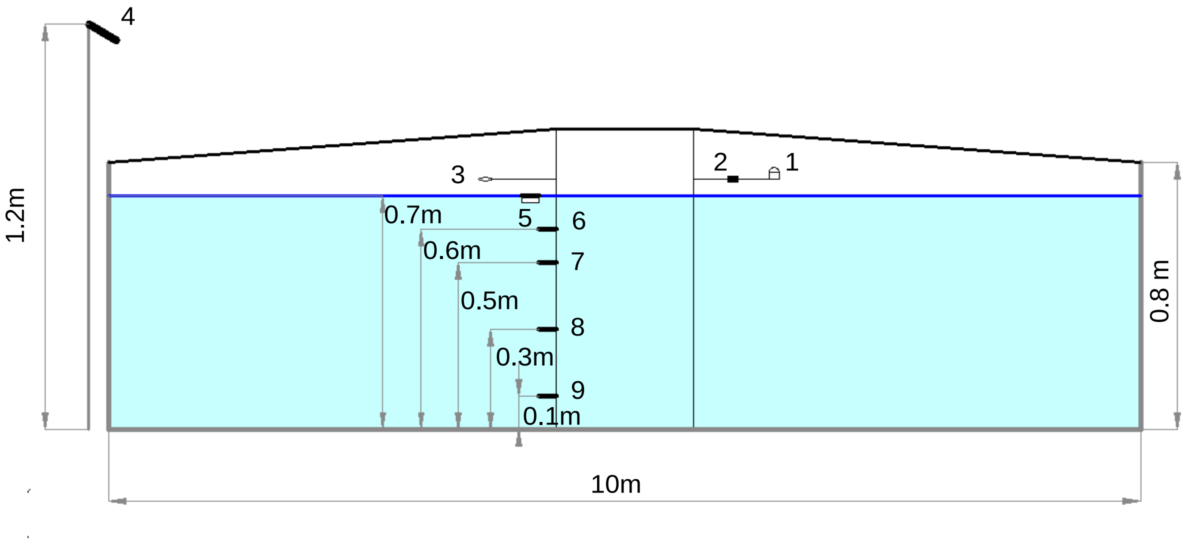
The evaporation rate, the meteorological variables and the water temperature profile were continuously registered during the trial. The evaporation rate, E_i (i = number of tank), was obtained from water level measurements performed with pressure transducers (PMP4030, Druck) submerged in the tanks and connected to a datalogger (GPL-80T, Kamel).

Water profile temperature was surveyed with copper-constantan thermocouples. Sensors were located at water surface ($T_{w0,i}$) and the following distances from the bottom: 0.6 m ($T_{w1,i}$), 0.5 m ($T_{w2,i}$), 0.3 m ($T_{w3,i}$), 0.1 m ($T_{w4,i}$) (Fig. 1). The incoming shortwave (R_s) and longwave (L_a) radiation were measured with the upward pyranometer and pyrgeometer respectively of a 4-component net radiometer (NR01, Hukseflux). An infrared temperature sensor (IRR-S, Apogee) gave the temperature of the cover, T_c, (assumed to be the same in tanks 1 and 2). Below the cover (b subscript) the following variables were registered: temperature, $T_{a,b,i}$, and relative humidity, $RH_{b,i}$, of inner air (HMP45C probe, Vaisala) in both covered tanks, net radiation in Tank 1 , $R_{n,b}$, (NRLITE, Kipp & Zonen) and transmitted solar radiation in Tank 1, $R_{s,b}$, (CM6B, Kipp & Zonen). The sensors were scanned at 10 s intervals, hourly averaged and registered by an automatic data logger (CR3000, Campbell Scientific) and multiplexer (AM16/32, Campbell Scientific).

An on-site automatic weather station (AWS) (Weathermaster 2000, Environdata) provided the following meteorological data: air temperature, T_a, and relative humidity, RH, solar radiation, R_s, and wind speed, U.

The data collection period was from 17/02/2010 to 23/02/2010. There were no rainfall events during the trial. This period is representative of the subtropical climatic conditions of south-eastern Queensland during the summer.

Figure 1 shows the experimental layout of Tank 1. The dimensions and placing of water temperature sensor for Tanks 2 and 3 is the same as Tank 1.



1: Pyranometer; 2: Air temperature and relative humidity probe; 3: Net radiation sensor; 4: Infrared temperature sensor; 5: Floating thermocouple; 6-9: Fixed thermocouples.

Figure 1. Experimental layout of Tank 1 (the vertical scale is exaggerated for clarity).

2.5. Calculation of R_n

Based on the fundamental physical laws of energy conservation, the radiative balance at the surface of the uncovered water body can be expressed as:

$$R_n = (1-\alpha)\ R_s + L_n \quad (1)$$

where R_n, is the net radiation at the water surface, α the albedo of the water (α=0.06), and L_n is the net long-wave radiation. L_n is the difference between the downward atmospheric radiation (L_a) and the upward long-wave radiation emitted by the open water surface, L_w.

The Stefan-Boltzmann equation was used to calculate L_w:

$$L_W = \varepsilon_W \sigma (T_W + 273.2)^4 \quad (2)$$

where ε_w is the water emissivity (= 0.97) and σ the Stefan-Boltzmann constant (= 5.68 10^{-8} W m^{-2} K^{-4}).

The net radiation at the water surface of the covered reservoir, $R_{n,b}$, was measured with a net radiation sensor. $R_{n,b}$ corresponds to the following radiation balance:

$$R_{n,b} = R_{s,b} + L_{n,b} \quad (3)$$

Below the cover only the solar radiation transmitted by the cover, $R_{s,b}$, reaches the water surface. The net long-wave radiation below the cover, $L_{n,b}$, is the difference between the downward radiation emitted by the cover and the upward long-wave radiation emitted by the water surface. $R_{n.b}$ can be assumed to be the same for Tank 1 and 2 since the cover is the same in both tanks, hence it has the same temperature, and the water surface was observed to have the same temperature in both tanks.

3. Results and discussion

3.1. Net radiation reduction

The shade cloth was observed to transmit just 1% of the incident radiation due its high solar absorbency. The average daily R_s during the trials was 302.86 W m^{-2} while $R_{s,b}$ was only 3.84 W m^{-2}. The minimization of R_s is the key feature of the cover to reduce the net radiation on the water surface. Fig. 2 shows the decrease of net radiation in covered tanks. The average reduction of net radiation for the trial period was 85%.

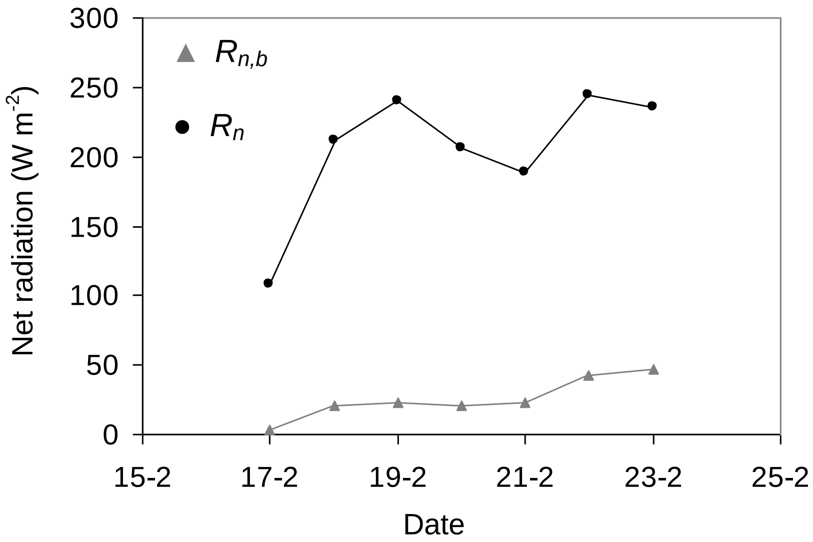


Figure 2: Comparison of net radiation in the covered ($R_{n,b}$, Tank 1 and 2) and uncovered tank (R_n, Tank 3)

3.2. Water profile

Apart from minimizing the solar radiation, the cover shelters the water surface from wind. As a consequence, the covered tanks presented stratification of the water temperature profile. Fig. 3 depicts the water profile of Tank 1 (covered) and 3 (uncovered). Tank 1 and 2 presented the same water temperature profile.

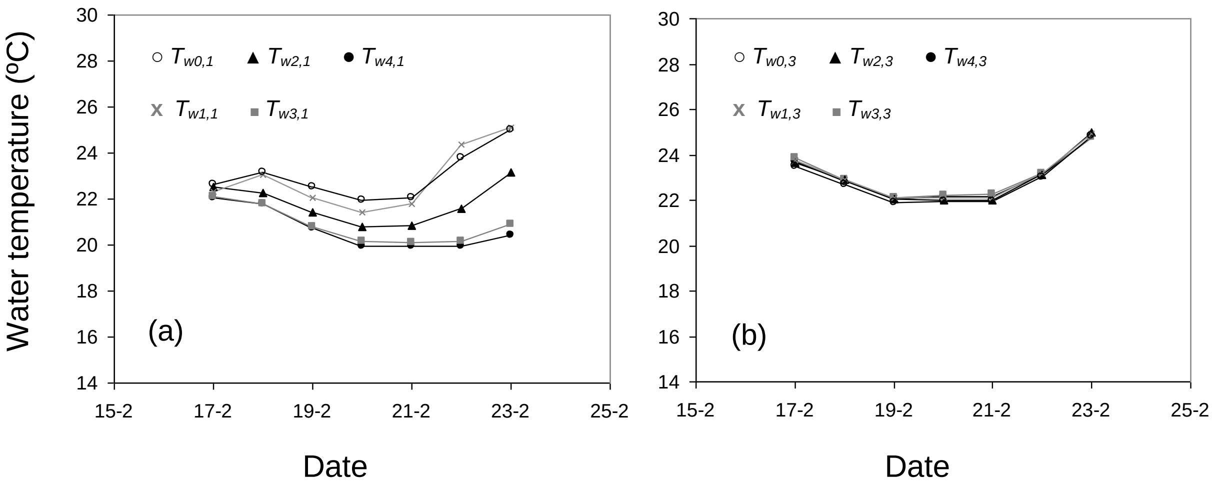


Figure 3: Water temperature profile of (a) Tank 1 (covered) and (b) and Tank 3 (uncovered)

A clear stratification process was observed in the covered tanks whereas the uncovered tank remained isothermal. At the end of the trial, after seven days, the temperature gradient in the covered tank from water surface ($T_{w0,1}$) to bottom ($T_{w4,1}$) was 4.6 ºC. Although the water surface temperatures in the uncovered and covered tank were similar during the experimental period, the cooling of the deeper layers in covered tanks meant that less thermal energy was stored in the covered tanks.

3.3. Microclimate below the cover

The cover modified the properties of air surrounding the water surface. The inner air (i.e. below the cover) daily temperature was on average 5 ºC above the outside air temperature registered in the meteorological station (Fig. 4). This is the consequence of the heating of inner air by the cover which reached very high temperatures (55ºC) at noon. In normal conditions, the water surface temperature is above the air temperature, so the water body heats the surrounding air; hence there is a sensible heat loss from the water surface. In the uncovered tank, the difference between the air temperature above the water and the surface temperature (T_a – $T_{w0,3}$) was less than zero (Fig. 4). However, in the covered tanks, the differences ($T_{a,b}$ – $T_{w0,1}$) and ($T_{a,b}$ – $T_{w0,2}$) were greater than zero, plus there was no evidence of a surface temperature increase in association with the maintenance of the condensed monolayer applied to Tank 2. These results are consistent with the observation that a condensed monolayer at the water surface reduces (conductive) sensible heat transfer as well as latent heat transfer (departure of energetic water molecules, i.e. evaporation). It is also recognised that monolayers can change the convective flux between the surface film and subsurface water by causing a change in the thickness of the diffusion layer. However, if the diffusion layer under the covers is already thick, the small change in the pressure gradient induced by maintaining a condensed monolayer at the surface may be insufficient to affect surface temperature.

The relative humidity of the air next to water surface was lower than the values measured in the AWS. On average, daily mean *RH* of the outside air was 15% above RH_b in covered tanks. However it should be noted that the absolute humidity of the inner air (12.00 g/kg) was above the ambient air (11.31 g/kg).

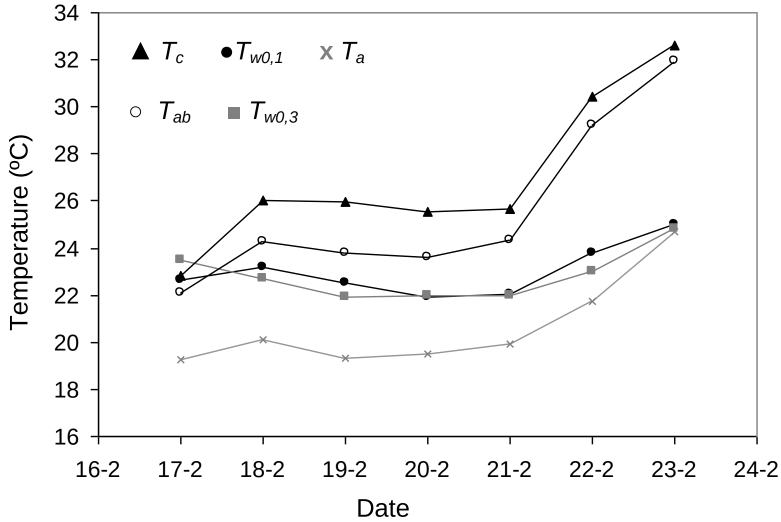


Figure 4: Cover temperature (T_c), air temperature below the cover ($T_{a,b}$) and in the meteorological station (T_a) and water surface temperature in the covered ($T_{w0.1}$) and uncovered ($T_{w0,3}$) tanks.

3.4. Evolution of water height

The evolution of the daily evaporated water height for the covered (E_1, E_2) and uncovered (E_3) conditions is depicted in Fig. 5.

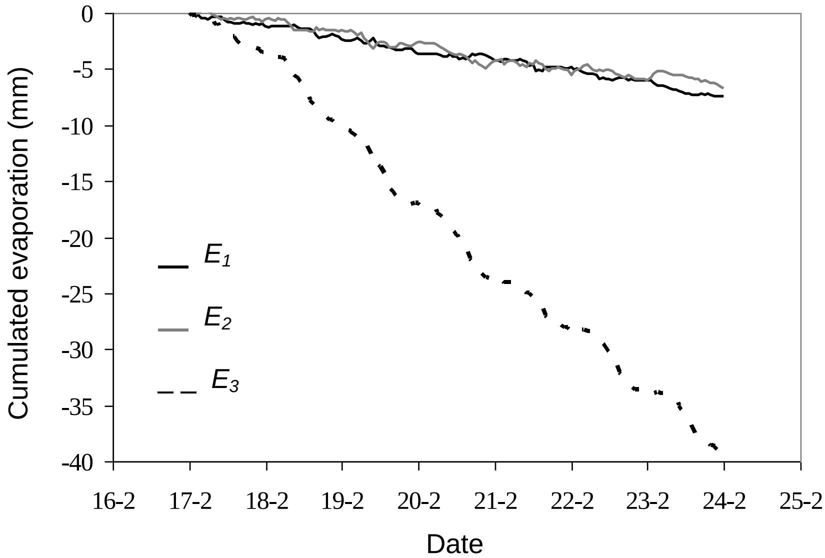


Figure 5: Evolution of the water height of covered tanks, E_1 (only covered) and E_2 (covered and monolayer applied) and uncovered tank (E_3). Lines are drawn from hourly data.

During the experimental period, the total decrease of water level of the uncovered tank was 39.55 mm whereas the covered tanks, Tank 1 and 2, only evaporated 7.38 and 6.69 mm, respectively. Hence, the evaporation reduction factors were 81.5% and 83% for Tanks 1 and 2 respectively. Note that this reduction is close to the reduction in net radiation (85%). These results corroborate the good performance of the ATARSUN cover (double black polyethylene cloth) already observed in south-eastern Spain (Martinez-Alvarez et al., 2010). However, the addition of the tested monolayer formulation (octadecanol in suspension with water and Brij 78 surfactant) did not significantly enhance the water-saving efficiency of the shade cover.

From the air-water temperature difference data (Fig. 4) it appears reasonable to attribute this result to the presence of the ATARSUN cover changing the local environment such that the evaporation control mechanism of the monolayer produces no significant additional evaporation-control benefit. As noted above, the applied monolayer has a wave-calming effect that contributes to evaporation reduction in open-water conditions, but in this experiment the cover sheltered the water surface from wind so there were no waves, i.e. the water was close to stagnant. Hence, the wave calming effect (which acts to increase the thickness of the gaseous diffusion layer is effectively inoperative. Furthermore, if the diffusion layer above the near-stagnant water surface was already thicker than the change induced by applying the monolayer, no significant reduction in evaporation would be expected.

4. Conclusions

The following conclusions can be drawn from this study:

- A reduction of 81-83% in evaporation rate was achieved by the ATARSUN cover under the summer climate conditions of south-eastern Queensland.

- The evaporation mitigation efficiency of the cover can be mainly ascribed to the high reduction of net radiation.

- The addition of the monolayer octadecanol (applied in suspension with water and Brij 78 surfactant), did not significantly improve the evaporation-control efficiency of the ATARSUN cover. This could be attributed to the fact that the ATARSUN cover produced a substantial 'stagnant' diffusion layer that any further enhancement (thickening) of this layer by action of the monolayer was insignificant.

5. Acknowledgements

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