Evaporation mitigation by floating modular devices

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Abstract. Prolonged periods of drought and consequent evaporation from open water bodies in arid parts of Australia continue to be a threat to water availability for agricultural production. Over many parts of Australia, the annual average evaporation exceeds the annual precipitation by more than 5 times. Given its significance, it is surprising that no evaporation mitigation technique has gained widespread adoption to date. High capital and maintenance costs of manufactured products are a significant barrier to implementation. The use of directly recycled clean plastic containers as floating modular devices to mitigate evaporation has been investigated for the first time. A six-month trial at an arid zone site in Australia of this potential cost effective solution has been undertaken. The experiment was performed using clean conventional drinking water bottles as floating modules on the open water surface of 240-L tanks with three varying degrees of covering (nil, 34% and 68%). A systematic reduction in evaporation is demonstrated during the whole study period that is approximately linearly proportional to the covered surface. These results provide a potential foundation for robust evaporation mitigation with the prospect of implementing a cost-optimal design.

1. Introduction
Climate change is now recognised as one of the greatest potential challenges to human society and industry [1, p 12]. Water security is under threat in the arid and semi-arid regions during drought due to changes in precipitation or evaporation from open water bodies. For example, it is recognised that the eastern half of Australia was systematically drier from 1895–1948 than during 1948–2000. However, rainfall has been below long term averages across much of southeast Australia since 1997 [2].

In many arid and semi-arid regions, the primary source of water is from many small farm dams. Consequently, minimising water losses from such dams is fundamental to the ongoing economic viability of farm production in arid areas. Construction costs and the energy intensity of pumping water long distances may make supply of water from more well-watered regions infeasible. As Weeks [3] stated, “Considering the importance of evaporation in the water balance of reservoirs, it is surprising that so few detailed research projects have studied the problem.”

The principal strategy in evaporation reduction is the minimisation of the water surface area that is in contact with the air as well as sheltering the water surface from the solar radiation [4, p 235]. Effective economic ways to reduce evaporation from large water bodies are yet to be developed [4, p 56].

Proposed open water evaporation mitigation techniques include wind sheltering by trees [5], (although, to our knowledge effectiveness has never been quantified); reservoir deepening [4, p 57],
unquantified); sand storage dams / managed aquifer recharge; chemical monolayers; continuous coverings of the entire reservoir and floating modular devices.

Use of sand storage dams for conserving water has been one of the successful methods in mitigating evaporation [6–9]. Thesis studies show that evaporation can be eliminated if the water level is kept below 1 m [8] from the top of sand surface. However, the main limitations of such storages are their potentially low specific yield from the artificial aquifer [9]. Although attempts to increase the specific yield by improving gradation have been made by [9], specific yield never exceeds 47%. In addition, there may be risks (physical human and animal safety, contamination, poor water quality) associated with groundwater dams, some of which still may not yet have been identified [9]. Furthermore, managed aquifer recharge, groundwater dams may be compromised by large plants directly extracting water from the alluvium. Sand storage dams are used in ephemeral African streams [10].

Extensive research has been undertaken on retardation of evaporation using monolayers. Conventional monolayers are thin chemical films that produce a diffusion barrier on the water surface [11]. Conventional monolayers are principally long chain alcohols. Vines and La Mer [12] demonstrated a reduction of evaporation using cetyl alcohol during field studies over a three-year deployment at Stephen’s Creek Reservoir, Broken Hill; Umberumberka Reservoir, Broken Hill, NSW; Lake Corella, Mary Kathleen, Queensland and several other places throughout Australia. They demonstrated an overall reduction of evaporation, but monolayer efficiency reduces with wind speed; approximately 40% when the wind speed is below 5 mph; 20% as the wind speed approaches 10 mph; and no reduction if it exceeds 15 mph. The application of the slurry was a very time consuming and expensive task. Crow [13] proposed open wind baffles arranged in the grid network to hold the monolayer during strong winds. Crow [13] showed that using low length/height ratios for closed wind barriers would lead to 32% reduction in evaporation if wind speed exceeds 5 mph. Wind-generated, microscale breaking waves develop when wind speeds exceed approximately 5 m s⁻¹. Peirson and Banner [14] demonstrate that strong subduction of the water surface occurs beneath the spilling regions of these small waves. In addition, wind waves compress and stretch the open water surface potentially tearing any surface films present [15]. Therefore, monolayers cannot remain effective in mitigating evaporation once microscale breaking waves form. Most commonly used monolayer materials are also quite readily broken down by bacteria [16] and hence reapplication is necessary at regular intervals (typically 1–3 days) to maintain a surface cover. Monolayer materials adhere preferentially to dusts, which may reduce their efficiency [17].

Continuous physical coverings (solid roofs, plastic covers, Evap-mat, aquaspan, super-span, NetPro shade cloths, E-VapCap, etc.) should reduce evaporation by 100% [18–24]. Although reservoirs of approximately 0.16 km² have been covered in Australia, such undertakings are a major engineering enterprise [25]. The specific challenge associated with such activities is maintaining reservoir cover integrity as water levels rise and fall. High installation cost, potential water quality effects, and wind induced forces may also be significant.

Reduction of exposed surface area by floating barriers has been proposed [26–29]. However, to our knowledge no systematic study has been published to ensure the effect of degrees of surface coverings (from partly covered to almost fully covered). Moreover, high installation and maintenance cost due to breakage of continuous blocks have also hindered the development. Proposals that reservoir could be partially covered due to either economic or physical constraints has been challenged by Watts [30] on the basis that there are no data to support that it could be a linear relationship between partial coverage and evaporation mitigation.

This present contribution critically examines the potential of floating modular devices to mitigate evaporation from open water bodies. Evaporation mitigation was quantified during field experiments undertaken at an Australian inland site over a six-month period spanning autumn to spring. These included testing the effects of partial covering and determining the corresponding pan coefficients.
2. Field facility and methodology

2.1 Test facility
The experiments have been set up at Fowlers Gap Arid Zone Research Station (only Arid Zone Research Station in Australia, Latitude: 31.37°S, longitude: 141.659°E; altitude 181 m above MSL and 110 km north of Broken Hill Town), New South Wales, Australia. The topography is such that the station is surrounded by hills and the nearest coastline lies approximately 500 km southwest. Meteorological data were obtained from Fowlers Gap Weather Station located 60 m from the site. Polyethylene tanks of 240-L capacity (600 mm x 500 mm x 1000 mm) were fitted with a 150-mm diameter PVC well to maintain water levels in the tank. Three tanks were buried 100 mm apart and levelled with their lips approximately 150 mm higher than the adjacent ground level to minimise splashing from the tank [31]. The tanks were filled up with water to match the level of the adjacent ground surface and the free surfaces were covered with different numbers of floating modular devices. One tank was left uncovered as reference. A second was covered with eight 600 ml standard drinking water bottles to cover approximately 34% of the free surface area. The third tank was covered with sixteen bottles to cover approximately 68% surface area. The top of the tanks were covered with 12 mm x 12 mm open wired mesh to prevent access by birds or animals.

Acoustic sensors (mic+30/IU/TC/E, Microsonic GmbH & Co, Germany; measuring range 60–350 mm) were used to record the wells. They were mounted in 147mm perplex disc which was screwed within the tube and minimised humidity exchange between the well air chamber and the ambient air. The perplex discs provided just sufficient ventilation to avoid any pressure anomaly within the well cavity. Those sensors were connected to a National Instrument Data Acquisition system (PCI-6221) fitted to a standard personal computer. Rainfall was monitored by a laser precipitation monitor (LPM Model 5.4110.00.000 manufactured by Adolf Thiess GmbH & Co, Germany) connected to the same computer.

Figure 1. Map showing location of the experimental site

Figure 2. Picture showing experimental set-up
2.2 Test procedure
The water levels at different tanks were recorded in the form of voltages from LabVIEW signal Express at 0.5-s intervals on real time basis (one million measurements over 6 days for each sensor). HyperTerminal was used to record the rainfall amount and rain droplet size distribution in every minute. Regular monitoring using TeamViewer was undertaken remotely to maximise data capture. Tanks were refilled to ensure that the water levels remained in proximity of the adjacent ground surface level. Calibration equations were developed for each sensor to correlate between the voltages and distances at the start of the experiment and another calibration was performed at the end of the study period. Over the monitoring period, the maximum change in gain observed was less than 1.5%.

2.3 Data analysis
Diurnal effects were eliminated by determining daily evaporation rate by conventional linear regression [32] to the 24 hours of data from midnight to midnight. For each data point, 90% confidence intervals were also calculated.

Evaporation mitigation efficiency has been quantified as the evaporation rate from each covered tank (34% and 68% coverage) as a proportion of the corresponding reference (uncovered) tank.

3. Results and discussion
Figure 3 shows that evaporation rates from tanks and amount of rainfall received by the arid zone during the test period. Seasonal effects on evaporation rates from the reference tank are also evident.

Figure 3. Top panel: Daily measurement of evaporation from the three tanks during the study period (March–September 2014). 90% confidence intervals are shown as error bars [upward pointing hollow triangles: Reference tank evaporation; downward pointing solid triangles: 68% covered tank; pluses: 34% covered tank]. Solid bars show periods of missing data. Due to sensor malfunction in the 34% covered tank, data after July have been discarded from all the analysis later than this period. Bottom panel: daily rainfall measurement from the LPM and the Fowlers Gap weather station.
During early autumn, evaporation rates were higher than rest of the period. During most of the study period, average daily evaporation was approximately 5 mm/hr. Due to an unknown problem in the sensor cable of the 34% covered tank after June 2014, evaporation measurements for that tank were excluded from rest of the analysis (figure 4).

For two months of study, it was observed that 34% coverage by plastic bottles reduced the evaporation rate by approximately 19% ± 1%. Across the suite of tests, evaporation mitigation efficiency of 68% coverage was consistent for most of the experimental duration, with an average reduction rate of 43% ± 1% (figure 4).

By linear extrapolation of the evaporation reduction rate to 95% coverage, it is estimated that evaporation could be mitigated by 58% for a single layer of 65-mm drinking water bottles. The mean measured mitigation rates at this site for the partially covered tanks are as shown in figure 5 in comparison with the recent study by Hassan et al. [33].
4. Conclusions and recommendations
The effectiveness of near zero cost and widely available recycled material in the form of floating modules to reduce evaporation has been performed in the field. The results obtained are consistent with the conclusions of Hassan et al. [33] that evaporation loss reduces approximately linearly in proportion with the degree surface covering. Long-term deployments have demonstrated that the results are robust across a range of climatic conditions.

Full scale field testing on real farm dams and possible water quality impacts in partially covered tanks should be investigated.

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