

Evaporation Reduction by Monolayers: Overview, Modelling and Effectiveness

David McJannet, Freeman Cook, John Knight and Stewart Burn

July 2008



Urban Water Security Research Alliance
Technical Report No. 6

Urban Water Security Research Alliance Technical Report ISSN 1836-5566 (Online)

Urban Water Security Research Alliance Technical Report ISSN 1836-5558 (Print)

The Urban Water Security Research Alliance (UWSRA) is a \$50 million partnership over five years between the Queensland Government, CSIRO's Water for a Healthy Country Flagship, Griffith University and The University of Queensland. The Alliance has been formed to address South-East Queensland's emerging urban water issues with a focus on water security and recycling. The program will bring new research capacity to South-East Queensland tailored to tackling existing and anticipated future issues to inform the implementation of the Water Strategy.

For more information about the:

UWSRA - visit <http://www.urbanwateralliance.org.au/>

Queensland Government - visit <http://www.qld.gov.au/>

Water for a Healthy Country Flagship - visit www.csiro.au/org/HealthyCountry.html

The University of Queensland - visit <http://www.uq.edu.au/>

Griffith University - visit <http://www.griffith.edu.au/>

Enquiries should be addressed to:

The Urban Water Security Research Alliance

PO Box 15087

CITY EAST QLD 4002

Ph: 07-3247 3005; Fax: 07-3405 0373

Email: Sharon.Wakem@qwc.qld.gov.au

Citation: McJannet, D., Cook, F., Knight J. and Burn, S. Evaporation reduction by monolayers: overview, modelling and effectiveness. CSIRO: Water for a Healthy Country National Research Flagship. Urban Water Security Research Alliance Technical Report No. 6.

Copyright and Disclaimer

© 2008 CSIRO To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO.

Important Disclaimer:

UWSRA and its partners advise that the information contained in this publication comprises general statements based on scientific research and does not warrant or represent the accuracy, currency and completeness of any information or material in this publication. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No action shall be made in reliance on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, UWSRA (including its Partner's employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Cover Photograph:

From CSIRO's ScienceImage: www.scienceimage.csiro.au

File: BU5045.jpg

Description: Googong Reservoir, Molonglo River, NSW.

Photographer: Willem van Aken

© 2008 CSIRO

ACKNOWLEDGEMENTS

Funding for this research was provided by the Urban Water Security Research Alliance.

Geoff Barnes, Nigel Hancock, Pam Pittaway and many others provided valuable inputs to improve the quality of this report. We thank David Rassam and Erik Schmidt for their constructive reviews of this report.

FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South-East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a \$50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at <http://www.urbanwateralliance.org.au/about.html>.



Chris Davis

Chair, Urban Water Security Research Alliance

CONTENTS

Foreword	iv
1. Introduction	1
2. Mechanism for reducing evaporation.....	1
3. Effects of monolayers on evaporation	1
4. Evaporation model	4
4.1. Heat storage modification	4
4.2. Evaporation resistance modification	5
4.3. Modified Penman-Monteith model	7
5. Modelling procedures and assumptions.....	7
6. Modelling results	8
7. Commercially available products	10
8. Potential effects on storage water quality and biology	11
8.1. Gas transfer effects.....	12
8.2. Chemical breakdown effects.....	12
8.3. Changes to the energy balance	13
9. Cost effectiveness.....	14
10. Social impacts	16
11. Factors affecting efficiency and applicability.....	16
12. Suggestions for further research	16
13. Key Messages.....	17
14. References	18
Appendix A.....	21
Monolayer costing - Distributed Applicators.....	21
Monolayer costing - Aerial Application	23
Appendix B.....	24
How wind generates water waves, and the implications for evaporation reduction by monolayers.....	24

LIST OF FIGURES

Figure 1: Relationship between water body area and evaporation reduction for studies in Table 1.....	3
Figure 2: Relationship between study duration and evaporation reduction for studies in Table 1.....	3
Figure 3: Function for monolayer resistance (r_m) of monolayer as a function of wind speed (U). The relationship used in the modelling is shown on the graph.....	6
Figure 4: Model estimates of cumulative evaporation from Wivenhoe Dam without a monolayer, with a monolayer applied year round, and with a monolayer applied only during summer.....	8
Figure 5: Time series of cumulative evaporation reduction (% - relative to baseline) for Wivenhoe Dam with monolayer applied all year and monolayer applied only during summer.	9
Figure 6: Model estimates of surface water temperature for Wivenhoe Dam with and without a monolayer.	10
Figure 7: Saturated oxygen concentration (mg L^{-1}) as a function of temperature ($^{\circ}\text{C}$).	14

LIST OF TABLES

Table 1: Literature studies testing the effects of monolayers on evaporation from water bodies. NB this table does not include laboratory or evaporation pan studies.	2
Table 2: Commercially produced chemical layer products available in Australia	10
Table 3: Approximate cost of water saved through monolayer application based on the use of distributed floating applicators. Costs are presented for evaporation savings between 6% and 20% for a water body of 75 km ² . Prices for product application rates at manufacturer recommended levels and at three times recommended levels are also presented.	15
Table 4: Approximate cost of water saved through monolayer application based on the use of aerial spraying. Costs are presented for evaporation savings between 6% and 20% for a water body of 75 km ² . Prices for product application rates at manufacturer recommended levels and at three times recommended levels are also presented.	15

1. INTRODUCTION

Unprecedented drought conditions and a growing population are putting pressure on the water supplies of south-east Queensland (SEQ). In response, water management authorities are assessing all possible means by which to create a sustainable water supply in the region. This report has been prepared for the SEQ Urban Water Security Research Alliance for the purposes of assessing the potential for using chemical monolayers to reduce evaporation from major water storages. This report is one of a group of reports that assess the applicability of different evaporation mitigation techniques to SEQ water storage systems.

The aims of this report are to:

1. Review the literature on evaporation reduction by monolayers.
2. Construct an evaporation model which will enable us to determine the potential for monolayers to reduce evaporation in SEQ.
3. Determine the cost effectiveness of monolayers as a means to reduce evaporation losses.
4. Review literature on the water quality and biological impacts of monolayers and assess the potential social impacts.
5. Identify future research requirements for improving our understanding of the potential beneficial and detrimental effects associated with monolayer application.

2. MECHANISM FOR REDUCING EVAPORATION

Monolayers are chemical films one molecule thick (~2 millionths of a mm) which produce a diffusion barrier on the water surface. Most monolayers reported in the literature have been produced using compounds of long chain fatty alcohols such as cetyl and stearyl alcohol. Such compounds spread spontaneously on contact with water (La Mer, 1962). Application of monolayers increases the apparent surface boundary layer thickness, thereby, increasing resistance to evaporation. The most commonly used monolayer materials are quite readily broken down by bacteria (Chang et al., 1962) and hence reapplication is necessary at regular intervals (typically 1 to 3 days) to maintain a surface cover. Similar chemical films, best described as surface films because of their multiple molecule thickness, are also available. These surface films reduce evaporation by the same process as monolayers but their characteristics are less well known.

3. EFFECTS OF MONOLAYERS ON EVAPORATION

Studies of the effects of monolayers on evaporation go back nearly 100 years. Despite this long period of investigation we are not aware of any examples of large scale and sustained use of monolayers on water storages. A review of the literature has revealed a large range of evaporation reduction values (0% - 43%) as a result of application of monolayers to water bodies (Table 1). The differences in duration of studies, type of product applied, water body characteristics (e.g. size, depth, elevation, wave action), evaporation estimation techniques and local climatic conditions make it difficult to define specific reduction rates from application of monolayers, however, this same variation does highlight the importance of local factors to the monolayer performance.

Table 1: Literature studies testing the effects of monolayers on evaporation from water bodies. NB this table does not include laboratory or evaporation pan studies.

Study	Location	Water body size (km ²)	Duration	Evaporation reduction
Sutherland et al.(1957)	Stephens Ck Reservoir, Broken Hill	4	14 weeks	37%
Grundy (1957a; 1957b)	Reservoir 1, Nairobi, Kenya	0.004	4 weeks	24%
Grundy (1957a; 1957b)	Reservoir 2, Nairobi, Kenya	0.026	4 days	30%
Grundy (1958)	Malya Reservoir, Tanzania	0.5	10 days	11.5%
Harbeck and Koberg (1959)	Pond, San Antonio, Texas	-	3 Weeks	18%
Committee of Collaborators (1959)	Lake Heffner, Oklahoma	10	12 weeks	9%
McArthur (1960)	Reservoir, Spain	0.12	7 weeks	35%
McArthur (1960)	Reservoir, Spain	0.12	10.5 weeks	31%
Franzini (1961)	Stanford University, California	0.16	-	18%
Roberts (1962)	Lake 1. Illinois	0.01	Summer	43%
Roberts (1962)	Lake 2. Illinois	0.01	Summer	22%
Vines (1962)	Umberumberka Reservoir, Broken Hill	1-1.2	2 months	40% up 8 km/h 10-20% up to 16 km/h 0% above 24 km/h Average 10-20%
Bureau of Reclamation (1962)	Lake Cachuma, California	9.7	8 weeks	8%
Bureau of Reclamation (1962)	Sahuaro Lake, Arizona	4	7 weeks	14%
Fitzgerald and Vines (1963)	Stephens Ck Reservoir, Broken Hill	4	6 weeks	15-20%
Fitzgerald and Vines (1963)	Lake Corella, Queensland	2.4	130 weeks	20%
Walter (1963)	Buderi Tank, Poondi, Madras	0.1	3 years	20%
Crow (1963)	Reservoir, Oklahoma Agricultural Experiment Station	0.001	66 days	25%
Craig et al. (2005)	University of Southern Queensland, Australia	0.000078	Period 1 - 6 days Period 2 - 8 days Period 3 - 6 days Period 4 - 7 days Period 5 - 7 days	38% 17% 10% 38% 40%
Craig et al. (2005)	Capella	0.042	Period 1 - 9 days Period 2 - 8 days Period 3 - 7 days Period 4 - 8 days	0% 0% 0% 0%
Craig et al. (2005)	Dirranbandi, Cubbie Station, Australia	1.2	Period 1 - 5 days Period 2 - 10 days Period 3 - 8 days	31% 27% 0%

Figure 1 shows the relationship between water body area and reduction in evaporation for studies shown in Table 1. The most obvious characteristic of this figure is the small number of studies on lakes larger than 4km². Although not conclusive it also appears that there is a trend towards smaller evaporation reductions as water body area increases. The two studies on lakes of around 10 km² report evaporation reductions of around 10%. These relatively small reductions could be the result of problems encountered when trying to maintain a continuous monolayer on water bodies this size as a result of wind and wave action. It is worth noting that the area of Wivenhoe Dam at full capacity is 110 km²; far bigger than any lake previously studied.

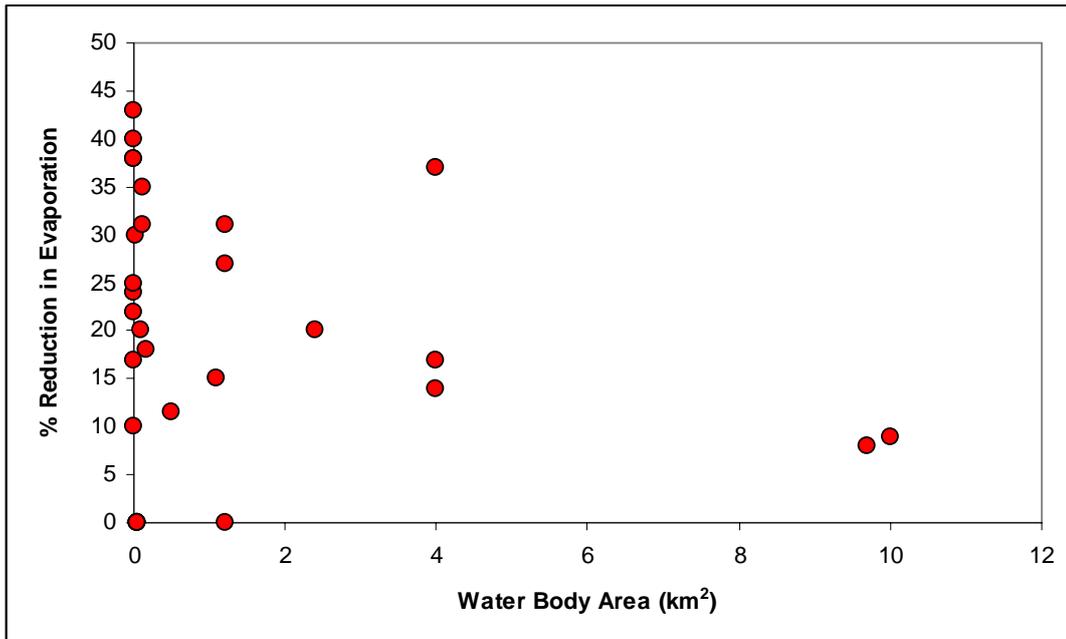


Figure 1: Relationship between water body area and evaporation reduction for studies in Table 1.

Comparison of the duration of studies with their reported evaporation reduction shows great variations between studies (Figure 2). Of particular importance is the fact that all but two studies were conducted for periods less than three months. As we will discuss and present below we believe that the transition of a water body from its original state to its new state of ‘equilibrium’ following monolayer application will take at least one month. If our model predictions are right then short duration studies need to be treated with great caution. The two long duration studies report evaporation savings of around 20%. It is worth noting that the review above deals only with monolayers, we could find no studies considering the impacts of surface films.

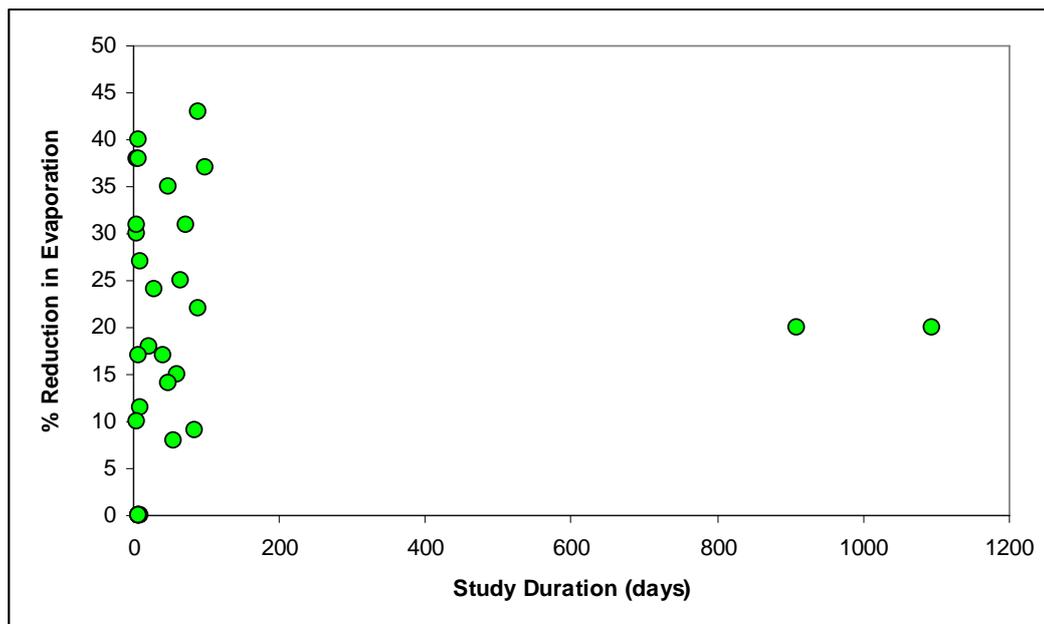


Figure 2: Relationship between study duration and evaporation reduction for studies in Table 1.

4. EVAPORATION MODEL

In order to assess the potential reduction in evaporation that could be achieved through application of a monolayer to a water body, it was necessary to develop a suitable evaporation model. To achieve this, we have chosen to build upon the widely applied Penman-Monteith model (Monteith, 1965). While the Penman-Monteith model was originally designed for determining the evaporation of water vapour from the sub-stomatal cavities of plants into the atmosphere it is flexible enough to use on water bodies through some modifications to the heat storage and resistance terms. We will describe these modifications below.

4.1. Heat storage modification

When applied to open water bodies, the Penman-Monteith approach must account for changes to the amount of energy available for evaporation based on changes in heat storage within the water body. To determine changes in the heat stored within the modelled water body between consecutive days, water temperature was estimated using the concepts of equilibrium temperature (e.g. de Bruin, 1982; Edinger et al., 1968; Keijman and Koopmans, 1973). The equilibrium temperature is defined as the surface temperature at which the net rate of heat exchange would be zero. In brief, the Penman-Monteith equation (Monteith, 1965) is used for a water body based on prescribed water surface temperature, air temperature, wind speed and vapour pressure.

The change in heat storage of the water body, N , is central to our open water evaporation model as it affects water surface temperatures and, hence, evaporation. The depth of a water body affects its potential to store energy, therefore, our model needs to be able to predict changes in this heat store between consecutive days. Within our model, changes to water temperature and heat storage are reliant on the equilibrium temperature (T_e) and the time constant (τ). The time constant controls the rate of change in water temperature between days as it dictates the time which would be required to reach equilibrium.

Water temperature, T_w (°C), is calculated from the following equation (de Bruin, 1982):

$$T_w = T_e + (T_{w0} - T_e) \exp(-1/\tau) \quad \text{Equation 1}$$

where -

T_{w0} is the water temperature at the previous time-step. The Equilibrium temperature, T_e (°C), is calculated from the following equation (de Bruin, 1982):

$$T_e = T_n + \frac{Q_n^*}{4\sigma(T_n + 273.15)^3 + f(U)(\Delta_n + \gamma)} \quad \text{Equation 2}$$

where -

T_n (°C) is the wet-bulb temperature,

Q_n^* (MJ m⁻² d⁻¹) is the net radiation at wet-bulb temperature,

σ (MJ m⁻² °K⁻⁴ d⁻¹) is the Stefan-Boltzmann constant,

$f(U)$ (MJ m⁻² d⁻¹ kPa⁻¹) is the wind function (see below),

Δ_n (kPa °C⁻¹) is the slope of the temperature saturation water vapour curve at air temperature, and

γ (kPa °C⁻¹) is the psychometric constant.

The time constant, τ , in days is calculated as follows (de Bruin, 1982):

$$\tau = \frac{\rho_w C_w Z}{4\sigma(T_n + 273.15)^3 + f(U)(\Delta_n + \gamma)} \quad \text{Equation 3}$$

where -

ρ_w (kg m^{-3}) is the density of water,

C_w ($\text{MJ kg}^{-1} \text{ }^\circ\text{K}^{-1}$) is the specific heat of water,

Z (m) is the depth of water, and

$f(U)$ ($\text{MJ m}^{-2} \text{ d}^{-1} \text{ kPa}^{-1}$) is a function dependant on wind speed (U).

The wind function, $f(U)$, is used in heat budget studies to define the evaporation rate from which latent heat loss is calculated. Studies from a number of different sized water bodies suggest that the evaporation coefficient should not only be a function of wind speed, but also of water body size. It seems that water body size affects the aerodynamic resistance to evaporative mass transfer. As air moves from the land across an evaporating water body, water is gradually evaporated into the air flow causing the humidity to increase with distance downwind from the shore. Consequently, this process tends to cause evaporation rate to decrease with distance downwind from a shore (Weisman and Brutsaert, 1974). However, as the air blows from land to water, the surface roughness reduces abruptly and wind speed and turbulence in the air flow gradually adjust to this change with increasing distance from the transition (Bradley, 1968). Both of these effects tend to cause variation in evaporation rate at increasing distances from a leeward shore and so we would expect that evaporation should vary with water body size (Giblett, 1921; Sartori, 2000). For our heat storage modification we use the area adjusted wind function developed by McJannet et al (2008a):

$$f(U) = A^{-0.05} (6.79 + 3.92U_{10}) \quad \text{Equation 4}$$

where -

U_{10} (m s^{-1}) is the wind speed at 10 m height, and

A (m^2) is the area of the water body.

Change in heat storage in the water body, N ($\text{MJ m}^{-2} \text{ d}^{-1}$), is then calculated from:

$$N = \rho_w C_w Z (T_w - T_{w0}) \quad \text{Equation 5}$$

The equilibrium temperature model employed utilises the same meteorological driving data as the Penman-Monteith model. Detailed description of the methodology employed are given in McJannet et al. (2008b).

4.2. Evaporation resistance modification

The aerodynamic resistance, r_a (s m^{-1}), of a water body without a monolayer applied can be defined by the following equation (Calder and Neal, 1984):

$$r_a = \frac{\rho_a C_a}{\gamma(f(U) / 86400)} \quad \text{Equation 6}$$

In order to determine the effect of the monolayer on evaporation we must add an additional resistance term. When a monolayer is applied to the water surface the boundary layer becomes thicker. However, there are a number of factors that govern the thickness of this layer and the effect it may have on resistance to evaporation. Early research (MacRitchie, 1968; MacRitchie, 1969) on monolayers suggested that a decrease in monolayer resistance with increasing wind speed was due to molecular chains tilting in the wind. Subsequent research (Barnes and Gentle, 2005) suggests that this is not the case and that in higher winds the monolayer tends to compress and occupy a smaller surface area. This results in the monolayer ‘collapsing’ and molecules being stacked on top of each other three or even five layers deep in some areas with no cover in others. The net effect of such a process across the water surface is a decrease in monolayer resistance at higher wind speeds and, hence, a reduced ability to decrease evaporation.

The evaporation resistance (r_m) imposed by different monolayer materials were measured by Navon and Fenn (1971b) in the laboratory under still conditions using the method developed by Navon and Fenn (1971a). The resistance imposed by different monolayers was measured by the change in surface tension. The maximum r_m for all of the monolayers tested was approximately 300 s m^{-1} , a value assumed by Mansfield (1972) and taken here as the maximum possible monolayer resistance (i.e. r_m when $U = 0 \text{ m s}^{-1}$).

A thorough search of the literature failed to identify any studies which report monolayer resistance as a function of wind speed. However, Fitzgerald and Vines (1963) gave the following reductions in evaporation due to cetyl alcohol based monolayer application at different wind speeds:

- $U \leq 2.24 \text{ m s}^{-1}$ evaporation savings of 40% or more;
- $2.24 < U < 4.47 \text{ m s}^{-1}$ evaporation savings of 10 – 20%; and
- $U > 6.71 \text{ m s}^{-1}$, evaporation savings approaching 0%.

From this we can infer that when wind speeds exceed 6.71 m s^{-1} the aerodynamic resistance of the monolayer is effectively zero. Thus, we have constructed a function for r_m , which is a linear relationship decreasing from 300 s m^{-1} for $U = 0 \text{ m s}^{-1}$ to zero for $U \geq 6.71 \text{ m s}^{-1}$ (Figure 3). It is acknowledged that the data used to form this relationship are very sparse, however we could find no better datasets on which to base our relationship. The change in monolayer resistance that we show in this figure can be seen as an average condition for the water surface which reflects the collapse of some areas of monolayer and exposure of the water surface in others (see Barnes and Gentle, 2005). This is definitely an area that warrants further research.

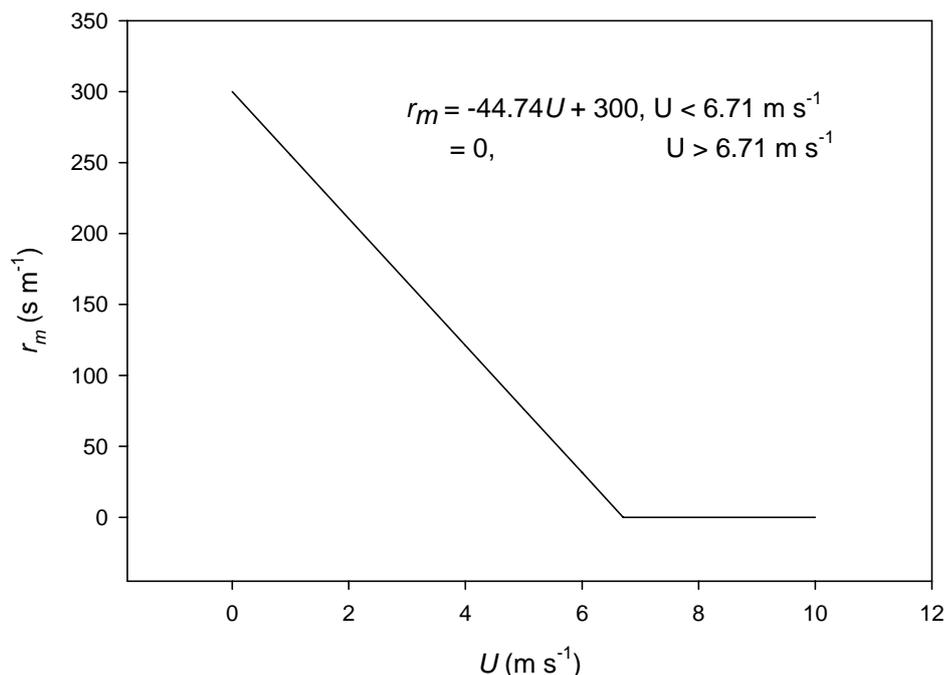


Figure 3: Function for monolayer resistance (r_m) of monolayer as a function of wind speed (U). The relationship used in the modelling is shown on the graph.

A linear function has been used for our modelling as no information is available to justify a more complicated function. Barnes (1993) used a constant value of r_m to show the possible effects of temperature and humidity on evaporation. Our specification of the effect of monolayers on evaporation resistance (Figure 3) as a linear function of wind speed is based on just one study for which the uncertainty in measurements is not known. The study used was also based around effectiveness of cetyl alcohol monolayers and it is likely that effects on aerodynamic resistance will vary with product used. Obviously, reliance on one study is risky therefore further research on the shape and magnitude of such relationships is essential to improve our predictive power.

4.3. Modified Penman-Monteith model

Based on the modifications to the Penman-Monteith model inputs described above, evaporation rates, E (mm d^{-1}), for a water body with a monolayer can be predicted by using the following equation:

$$E = \frac{1}{\lambda} \left(\frac{\Delta_w (Q^* - N) + 86400 \rho_a C_a (e_w^* - e_a) / (r_a + r_m)}{\Delta_w + \gamma} \right) \quad \text{Equation 7}$$

where -

λ (MJ kg^{-1}) is the latent heat of vaporisation,

Δ_w ($\text{kPa } ^\circ\text{C}^{-1}$) is the slope of the temperature saturation water vapour curve at water temperature,

Q^* ($\text{MJ m}^{-2} \text{d}^{-1}$) is net radiation,

N ($\text{MJ m}^{-2} \text{d}^{-1}$) is change in heat storage in the water body,

ρ_a (kg m^{-3}) is density of air,

C_a ($\text{MJ kg}^{-1} \text{ } ^\circ\text{K}^{-1}$) is specific heat of air,

e_w^* (kPa) is saturated vapour pressure at water temperature, and

e_a (kPa) is vapour pressure at air temperature.

5. MODELLING PROCEDURES AND ASSUMPTIONS

As a test case, the model was applied to water body representative of Wivenhoe Dam in SEQ ($27^\circ 23' 24'' \text{S } 152^\circ 37' 8'' \text{E}$). The water body had an assumed surface area of 100 km^2 and an average depth of the well mixed surface layer of 5 m. We assume that this depth is constant over time but further studies would be needed to support this assumption.

The primary source of meteorological data is the SILO database which consists of interpolated meteorological variables on a 0.05° (5 km) grid for the whole of Australia (Jeffrey et al., 2001). The climate variables from SILO that were used by the evaporation model were air temperature, vapour pressure, and solar radiation. For evaporation modelling the SILO data drill was used to extract daily data for the Wivenhoe Dam area. Daily average wind speed data was taken from the nearest Bureau of Meteorology station. Wind speed data have been recorded at the reservoir but this data was not available at the time of writing.

We have used a 3 year record of climate data (1984-1986) from the SILO data drill and wind speed from Mt Nebo. These years were selected as they contained the only reliable and readily available wind speed data for this area. It is uncertain as to the degree that wind data from Mt Nebo are representative of that over the water body. When locally collected data becomes available a comparison is warranted.

Three scenarios are assessed using the evaporation model described above. The first is an analysis with no monolayer applied (baseline), the second is an analysis with monolayer applied throughout the year and the third is an analysis with monolayer applied only during the summer months (December to

March). The third scenario is targeted at reducing evaporation when it is at its greatest. Evaporation during December to March represents 43% of total evaporation. We assume that the monolayer is applied at a rate that ensures a continuous cover. For the monolayer products discussed in the literature the reapplication time is generally between 1 to 3 days.

It is also worth noting that our model assumes that the monolayer can respread across the water body following compression by wind and waves. In reality this is probably not likely to be the case, especially when the monolayer is deposited on the leeward shore or compressed in a small area at the upwind edge of the water body. This is a process which needs further investigation considering the fetch lengths and wind speeds likely on the major water storages in SEQ. The effect of wave action on evaporation rate is also not considered in the model although in reality small increases are likely to occur due to enhanced evaporation of wave spray and increased turbulence over the water surface.

6. MODELLING RESULTS

Over the three year model simulation the average annual evaporation for the untreated storage was 1560 mm. After application of the monolayer for the entire period, average annual evaporation was reduced to 1390 mm; a reduction of 11% (Figure 4). Interestingly, annual evaporation for the scenario where the monolayer was applied only during summer was 1482 mm, a reduction of 6%. This suggests that application of the monolayer for the other 75% of the year results in an additional evaporation reduction of only 5%.

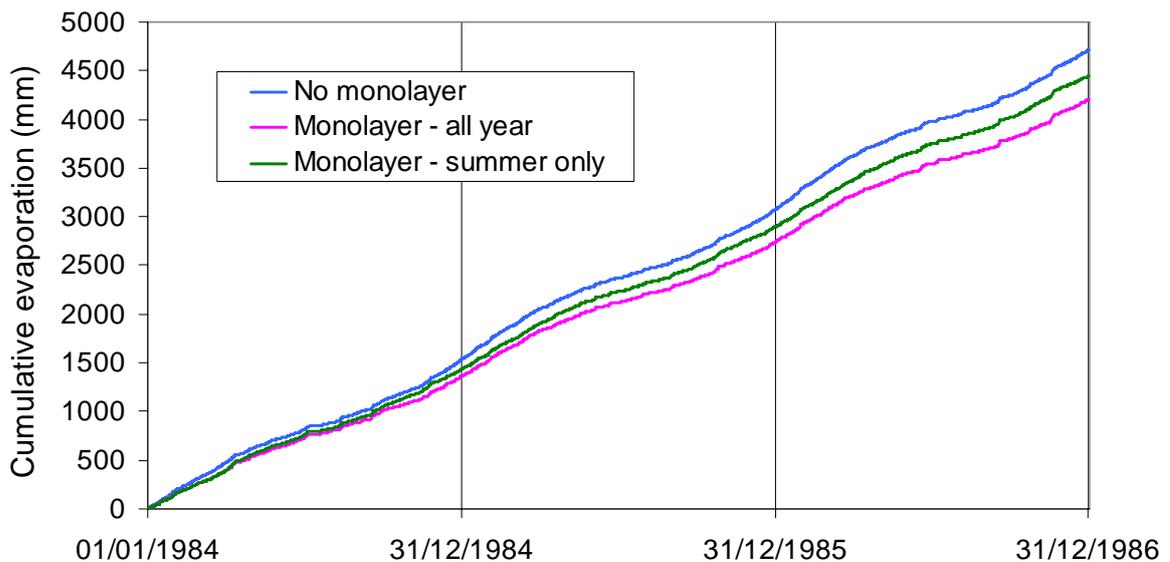


Figure 4: Model estimates of cumulative evaporation from Wivenhoe Dam without a monolayer, with a monolayer applied year round, and with a monolayer applied only during summer.

Comparison of the cumulative differences in evaporation between the dam with and without the monolayer reveals some interesting results which emphasise the importance of long term studies in providing realistic results (Figure 5). If the simulation was run for just 1 week the reported evaporation reduction would have been 31%, for one month the reduction would have been 26%, and for 3 months the reduction would have been 21%. These numbers are much higher than the 11% achieved for the duration of the three year model period. Considering that the vast majority of studies in the literature are for periods of less than 3 months these results need to be treated with some caution.

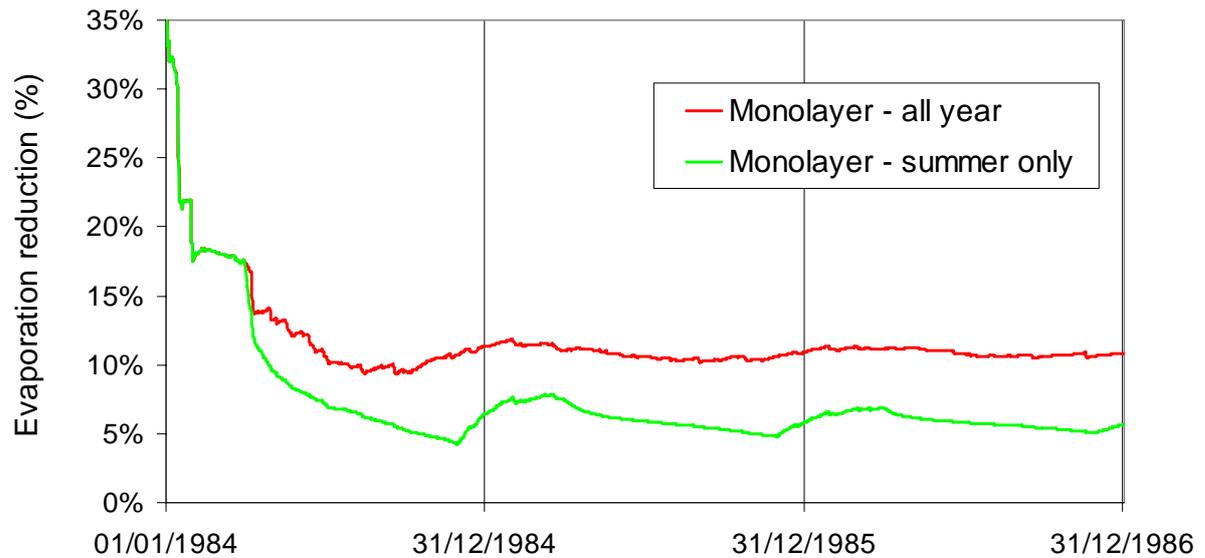


Figure 5: Time series of cumulative evaporation reduction (% - relative to baseline) for Wivenhoe Dam with monolayer applied all year and monolayer applied only during summer.

Addition of a monolayer to a water surface does not reduce the amount of incoming radiation entering the water body. The effect of the monolayer is to reduce evaporation. The process of reducing evaporation results in a decrease in energy loss from the water body which is manifested through an increase in water temperature (Figure 6). As water temperature is one of the key drivers of evaporation, the increased temperature produces a feedback whereby it is actually possible to get enhanced evaporation under the right conditions. The conditions for such an occurrence would include high radiation input and strong winds. Strong winds would reduce the effectiveness (aerodynamic resistance) and coverage of the monolayer, hence exposing the warmer water beneath. It is also interesting to note that the temperature rise as a result of monolayer application is greatest during the summer months.

Over the course of three years, the average water temperature rise for year round application was 2.2°C. During summer, the average water temperature increase compared to the baseline scenario was 3.0°C while in winter it was 1.0°C. Increases in water temperature will, of course, have impacts on water quality and this will be discussed later in this report. Similar changes in water temperature following monolayer application have been observed by Wolbeer (1963) and Harbeck and Koberg (1959). Over a 21 day study Harbeck and Koberg noted a 1.9°C increase in water temperature and an 18% reduction in evaporation. Over a 21 day period our model predicts a water temperature increase of 1.7°C for an 18% evaporation reduction giving confidence in our model predictions.

With the summer monolayer application scenario, water temperatures varied between the range of the other two scenarios (Figure 6). After commencement of the application of the monolayer during summer it took about one month for water temperatures to reach those attained in the all year application scenario. Similarly, at the end of the summer, it took about one month for temperatures to cool to those of the baseline scenario.

The other impact of the rise in water temperature is that when monolayer application is discontinued, evaporation will increase for a period, thereby reducing the true water savings. This is highlighted in a study from Lake Cachuma (see Wolbeer, 1963) where it was shown that if the evaporation reduction evaluation had been stopped with termination of monolayer application, the savings would have been over-estimated by 50%. This demonstrates that an accurate assessment of the performance of any short-term monolayer application should take into account the period following cessation of monolayer application when evaporation will be enhanced.

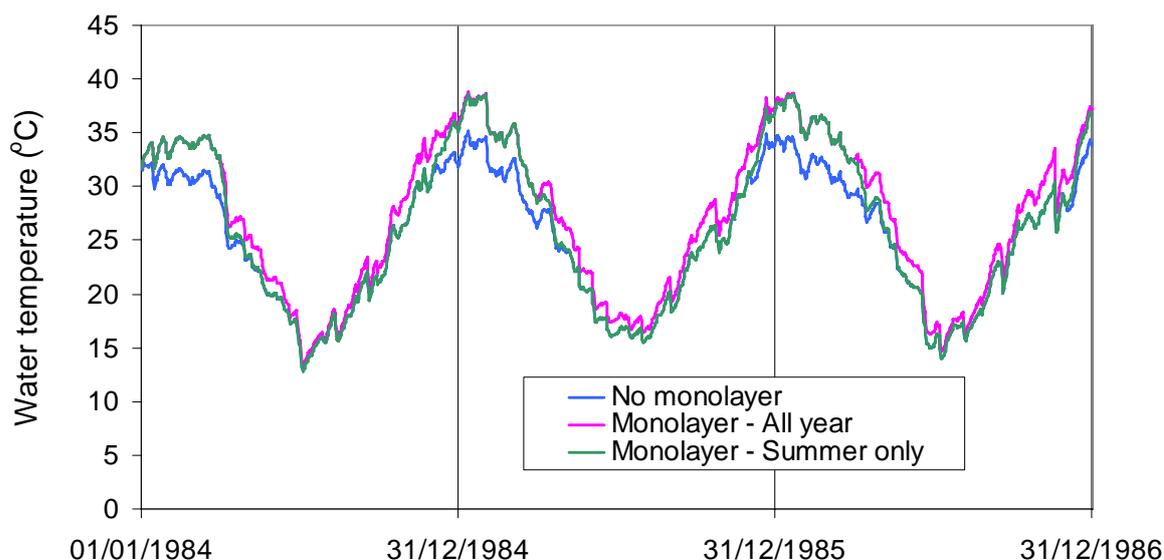


Figure 6: Model estimates of surface water temperature for Wivenhoe Dam with and without a monolayer.

While evaporation reduction predictions of around 11% are much less than the 30-50% reductions claimed by the manufacturers they still represent a significant savings for a water supply. However, a number of issues need to be addressed to improve confidence in these results. In particular, the ability of the monolayer to respread over large areas following wind and wave action needs to be addressed. It is believed that this could be the biggest impediment to effectiveness on water bodies with large fetches and high wind speeds such as we see in SEQ. Interested readers should see Appendix B for a review of wave generation and the implications for evaporation reduction by monolayers. If respreading is in fact hampered by wind and wave action on such large storages then the reductions in evaporation are likely to be much less.

7. COMMERCIALY AVAILABLE PRODUCTS

There are two main chemical film products available in Australia, these are Aquatain and WaterSavr. WaterSavr is a true monolayer product while Aquatain is better described as a surface film product. Another product, Hydrotect, has been found in the literature but approaches to the company for information failed to yield any responses. Details of the two products are given in Table 2.

Table 2: Commercially produced chemical layer products available in Australia

	Aquatain (surface film)	WaterSavr (monolayer)
Chemistry	Siloxane	Cetyl/stearyl alcohol
Approximate cost (bulk supply including GST)	\$16.00 per litre	\$10.00 per kg
Application rate	2 litres/ha	0.35 kg/ha
Re-application period	10 days	Daily
Claimed savings	50%	30%
Recommended application method	Aerial spraying	Applicator

Aquatain has claimed savings of 50% based on an independent trial conducted by Total Ag Services over a three week period at a 0.4 ha dam at Tarcoola near Dalby (Boshammer, 2007). As a control an evaporation 'tub' was used, however, this creates problems as a small container of water will evaporated at a faster rate than a larger water body. Assuming the evaporation tub was 1 m² we would expect evaporation to be 10-15% greater than a 0.4 ha dam. As a result we would consider the 50% reduction to be an over estimate. It is also worth noting that the independent trial used an initial dose of 7 litres/ha and a second dose of 3.5 litres/ha on day 9. Both of these dosages are well in excess of the recommended 2 litres/ha. In fact, even the lower dosage rate would result in a 75% increase in the cost of product for any treatment. Other researchers have noted the need to over-dose with chemical product to get decent results (Hancock and Barnes Pers. Comm.).

A study on the evaporation reduction achieved using WaterSavr on a 4 ha dam at Korong Vale over a 3 week period claimed evaporation savings of ~30%. Results were based on comparison with an almost identical and adjacent dam that was untreated (WaterSavr, 2006). This study also claimed no changes in water quality.

Reports for both products claim savings based on three week studies which we believe need to be treated with caution when estimating long-term savings on much larger storages. In this report we will demonstrate that impressive short-term evaporation savings soon reduce substantially as the treated water body obtains a new 'equilibrium' in response to energy balance changes.

Material Safety Data Sheets (MSDS) for the safe handling of these products are available from the suppliers.

Contact details:

Aquatain

Ultimate Agri-Products
03 9701 0544

WaterSavr

Phoslock Water Solutions
02 9453 0455

It is also worth noting that new monolayer products are currently being developed through the Cooperative Research Centre (CRC) for Polymers. A project within CRC for Polymers aims to create new monolayer chemicals which are more durable and more effective in reducing evaporation. Commercialisation of some of these products is still some time off.

8. POTENTIAL EFFECTS ON STORAGE WATER QUALITY AND BIOLOGY

The effects of application of monolayers and surface films on water quality are largely unknown and may vary on a storage by storage basis. Some researchers believe that the effects of monolayers on aquatic processes are relatively benign due to the fact that most water bodies already have naturally occurring microlayers that are formed by the break down of organic material (Norkrans, 1980). The earliest evidence for the existence of surface films was inferred from observations on the movement of dust particles on the surface as affected by water currents (Goldacre, 1949). Studies indicate that the thickness of these natural films varies from 100 to 500 nm (Munster et al., 1998). In contrast, artificial surfactant films may be 40-50 nm thick (Gladyshev, 2002). Any study on the longer term impact of artificial monolayers needs to compare their impact relative to local microlayers, and the impact of naturally occurring microlayers on the efficacy of artificial monolayers. If ecological 'equivalence' can be established, the adverse impacts should be minimal (Pittaway Pers. Comm.).

Potential water quality impacts fall in to three categories: those that result from breakdown of the chemical product itself; those that relate to changes in gas transfer across the air water interface; and those that result from changes to the energy balance of the storage.

8.1. Gas transfer effects

An effect of chemical layers is to increase the boundary layer thickness (δ) at the water surface (MacRitchie, 1969). The transfer of gases across the water surface in this boundary layer will be controlled by diffusion. The thicker the boundary layer the longer the path length will be and the larger the change in flux (J) and/or the concentration in the water phase (C_0), as can be seen by examination of Equation 8:

$$J = \frac{D(C_0 - C)}{\delta} \quad \text{Equation 8}$$

The changes are likely to cause dissolved carbon dioxide concentrations to increase and oxygen concentrations to decrease. The increase in carbon dioxide concentration could decrease the pH of the water. Decrease in oxygen concentration by diffusion will be mitigated by the oxygen production of algae. This could result in higher daytime concentrations of oxygen when algae are photosynthesising and lower night-time concentrations when algae are respiring. The thicker boundary layer due to a monolayer or surface film will result in possibly less diffusion of oxygen into or out of the water body depending on the time of day.

Blank (1962) analysed the effect of different monolayer types on the diffusion of different gases. The results of his laboratory analysis suggested that the effect of monolayers on oxygen and carbon dioxide exchange can be neglected. Similar findings were reported by Timblin (1957) and (Hayes, 1959), however other research (e.g. Downing and Melbourne, 1957; Hawke and Alexander, 1960) suggest that at higher gas transfer rates, monolayers considerably reduced the passage of oxygen and other gases. Wixson (1966) showed that at 20°C the application of a monolayer reduced oxygen diffusion by 10-15%, however effects varied with timing of measurements and duration of trials.

The inconsistent results with oxygen diffusion may relate to two factors; firstly some organic solvents such as n-hexadecane are known to act as an oxygen vector, increasing the oxygen available to microbes (Liu and Wu, 2006). Hexadecanol or its breakdown products may also improve the solubility of oxygen at the water interface. Secondly, hexadecanol and to a lesser extent octadecanol, are rapidly metabolized by adapted microbes, due to the similarity of their structure to C16 bacterial storage compounds (Pittaway Pers. Comm.). The subject of gas exchange processes warrants further long-term investigations.

8.2. Chemical breakdown effects

It has been suggested that bacterial activity is responsible for at least part of the degradation of monolayers. Silvey (1960) noted a pronounced increase in bacteria that feed on the monolayer chemicals and also reported “encouragement of growth of certain sedges by the deposition of solid recompressed chemical on the leeward shore”. Wixson (1966) also noted increased bacterial populations over the duration of trials as the utilised the monolayer as a substrate. Unfortunately, the monolayer selected for the earlier monolayer trials (hexadecanol), is also the most microbially labile of the long-chain fatty alcohols (Pittaway Pers. Comm.). Bacteria utilize polyhydroxyalkanoic acids, triacylglycerols and wax esters as storage lipids (Uthoff et al., 2005). Wax esters are oxoesters of primary long-chain fatty alcohols and long-chain fatty acids. In nature, long-chain fatty acids and alcohols are widespread in plant species, and may constitute from 2 to 70% of the cuticular wax composition of grasses (Dove and Mayes, 1991). Hydrophobic organic compounds in the microlayer are derived from debris in the catchment, and include n-alkanes, n-alkan-1-ols and sterols (Berdie et al., 1995). Relatively simple monolayer compounds such as hexadecanol are readily degraded, reducing their cost-effectiveness as evaporation retardants.

During large scale field tests at Lake Hefner in 1958 the influence of monolayer (hexadecanol) on water quality was carried out. Three months of monitoring revealed that there were no deleterious effects from the application of the monolayer (Matthews, 1959). Other studies which have looked at the effect of hexadecanol layers on fish, ducks and aquatic insects have failed to reveal any toxic effects (Hayes, 1959; Timblin, 1957). Another effect of monolayers on natural ecosystems could be

through the reduction in surface tension. Organisms dependant upon the support of the surface at various life stages may be adversely affected. This has been shown to be the case by Hayes (1959) with respect to the emergence of immature insects. The study of Wixson (1966) showed that the mixture of octadecanol and hexadecanol monolayers reduced surface tension, causing filamentous algae to sink. This same study also showed no effects of the monolayer on the fish species *Gambusia affinis* and *Fundulus notatus*.

The WaterSavr product is alcohol based and breaks down in sunlight to an acid and then final products of CO₂ and water. Permeability of the monolayer to CO₂ may be an issue as CO₂ in solution forms an acid which may affect pH. This product is claimed to be permeable to oxygen however it is uncertain as to over what time period effects on aquatic oxygen levels have been made. Further observations of this are required to justify this claim.

An assessment of the impacts of Aquatain on water quality was undertaken over a period of 16 days on a small dam near Silvan, Victoria (van de Graaff, 2007). This very short analysis of potable water criteria and silicon and methanol reported no significant impacts. The results do however report a decrease in pH over the 16 days (8.4 reduced to 7.45). This is dismissed as an effect of respiring aquatic organism, however, further investigation is required here as the change in acidity could be the result of increases in CO₂ in the water as a result of the breakdown in the silicon based chemical that forms this surface film. CO₂ in the presence of water can transform into carbonic acid. On the basis of 'incidental observations' of paramecium over the 16 days observation period, this study also concludes that Aquatain has no impact on oxygen and CO₂ exchange with the atmosphere and therefore has no effect on aquatic life.

It is believed that such claims are hard to substantiate given the short study period. It is worth noting here that Aquatain is a completely different chemical make to monolayers trialled in the past and as such many of the findings of previous studies do not necessarily apply to this product. The production of CO₂, which is a greenhouse gas, may also be of concern for this product given the areas to be treated and sustained nature of applications. It is worth noting that Aquatain has achieved NSA International certification (NSF/ANSI Standard 60 - Drinking Water Treatment Chemicals - Health Effects). This standard establishes minimum requirements for chemicals, the chemical contaminants, and impurities that are added to drinking water from drinking water treatment chemicals. Contaminants produced as by-products through reaction of the treatment chemical with a constituent of the drinking water are not covered by this standard. Details are available from the supplier.

A further area for consideration is the impact of water quality changes and the monolayer product itself (including breakdown products) on water treatment processes and costs. Some of the transformations possible due to monolayer application may reduce some treatment requirements while others may require further extra treatment. Either way a detailed analysis of effects on the water treatment process would be essential before full blown trials on potable water supplies. In these studies it would be necessary to determine the reaction of monolayer or surface film chemicals with membranes, filter media, chlorine, chloramines, fluoride, pH correction products, and alum.

8.3. Changes to the energy balance

Modelling results and field monitoring (Harbeck and Koberg, 1959; Wolbeer, 1963) suggest that water temperature will rise with application of monolayers and such changes are likely to impact upon chemical processes occurring in the water. The rise in temperature of the water has also been shown to reduce the effectiveness of the monolayer, with a reduction in the resistance at the same surface tension (Navon and Fenn, 1971b). Also, as the water temperature is raised the saturated oxygen concentration is decreased, which could lead to lower dissolved oxygen concentrations (Figure 7). Increased water temperatures also have the potential to increase the risk of algal blooms.

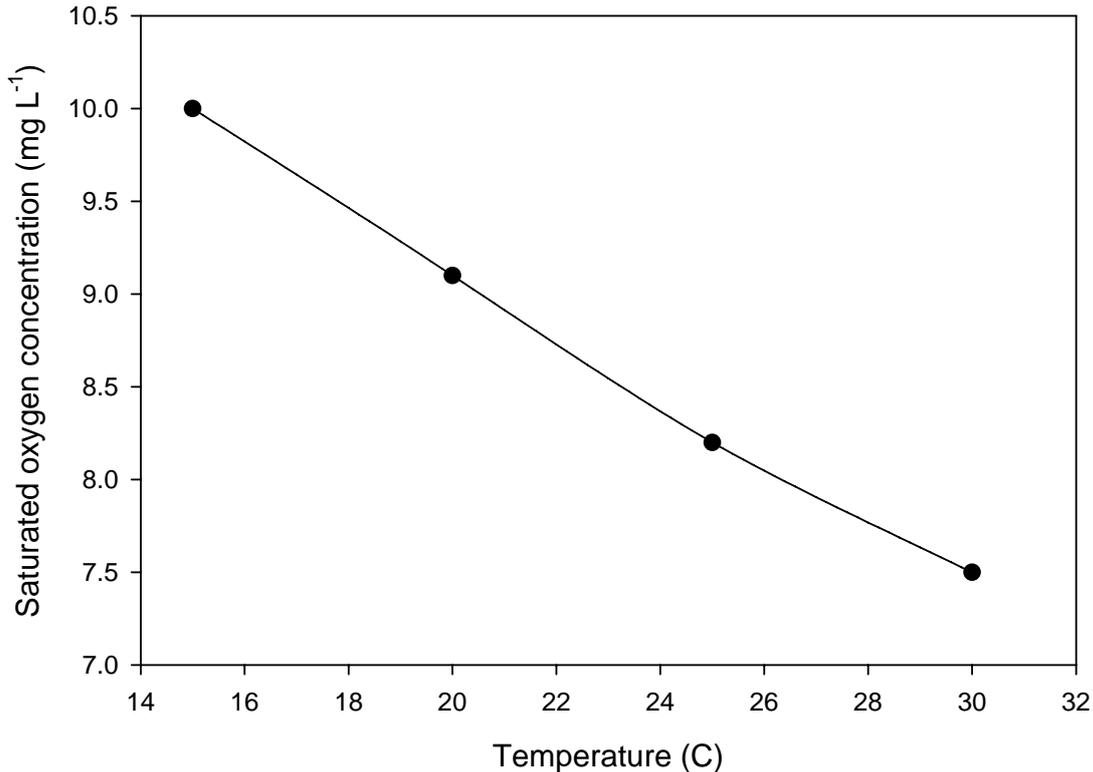


Figure 7: Saturated oxygen concentration (mg L⁻¹) as a function of temperature (°C).

In summer, the combined effects of high water temperatures and lower diffusive flux could result in changes in the oxygen concentrations in the water and may have biological consequences (i.e. algal blooms). These effects would need to be monitored over a reasonably long period of time in order to understand all of the nuances.

9. COST EFFECTIVENESS

While the ability of monolayers to reduce evaporation is fairly well established, the cost effectiveness for large scale storages has not been assessed. Using our literature review and model results, monolayer product and application costs, and estimates of transport, storage and salary costs, we can derive a price for the water saved via reduced evaporation. For this analysis we will use prices only for the WaterSavr product as it is the only true monolayer. The alternative product, Aquatain, is a surface film which has been subjected to very limited research. We will also only assess the scenario where the product is applied during the three summer months. We will report costs based on two different application methods: 1) commercially available applicators distributed around the dam (Table 3); and 2) aerial application using crop duster aircraft (Table 4).

Costs in these tables are calculated on an annual evaporation saving of between 95 mm and 310 mm which corresponds to the range of savings from our modelling our model (6%) and maximum published savings reported in the literature (40% - applied to summer months = 20% annual reduction), respectively. The figures in these tables are for a water body with an area of 75km² (average for Wivenhoe Dam for last 14 years). We have calculated two final pricings for water saved in each table, the first is the savings based on the manufacturers recommended application rates, and the second is the savings based on an application at a rate of three times that recommended. The pricing at three times the recommended rate are presented as an upper level following tests in the field (Erik Schmidt Pers. Comm.) which showed that the best performance was achieved at a dosing of three times the recommended rate. Part of this is believed to be due to compression of the monolayer over time. Details of the cost calculations for Table 3 and Table 4 are given in Appendix 1.

Table 3: Approximate cost of water saved through monolayer application based on the use of distributed floating applicators. Costs are presented for evaporation savings between 6% and 20% for a water body of 75 km². Prices for product application rates at manufacturer recommended levels and at three times recommended levels are also presented.

	Recommended Rate	3 x Recommended Rate
Evaporation savings	7,125 – 23,250 ML (6% - 20%)	7,125 – 23,250 ML (6% - 20%)
Product cost	\$3.15 M	\$9.45 M
Application cost	\$600 K	\$600 K
Storage facility costs	\$525 K	\$602 K
Transport costs	\$184 K	\$551 K
Salary/Office costs	\$416 K	\$1.247 M
TOTAL annual costs	\$4.875 M	\$12.45 M
Cost of water saved	\$0.21 - \$0.68 / kL	\$ 0.54 - \$1.75 / kL

Table 4: Approximate cost of water saved through monolayer application based on the use of aerial spraying. Costs are presented for evaporation savings between 6% and 20% for a water body of 75 km². Prices for product application rates at manufacturer recommended levels and at three times recommended levels are also presented.

	Recommended Rate	3 x Recommended Rate
Evaporation savings	7,125 – 23,250 ML (6% - 20%)	7,125 – 23,250 ML (6% - 20%)
Product cost	\$3.15 M	\$9.45 M
Application cost	\$3.486 M	\$3.990 M
Storage facility costs	\$256 K	\$256 K
Salary/Office costs	\$38.6 K	\$38.6 K
TOTAL annual costs	\$6.931 M	\$13.735 M
Cost of water saved	\$0.30 - \$0.97 / kL	\$0.59 - \$1.93 / kL

Table 3 and Table 4 show that the range in cost of water saved is quite large depending on whether evaporation savings of 6% or 20% occur or whether recommended application rates or rates three times those recommended are used. Interestingly there is not much difference in the costs of water saved if distributed applicator systems of aerial spraying methods are used. While we have reported a range of cost figures we believe that dosage rates should be higher than manufacturer recommendations to ensure complete coverage. We also believe that evaporation reductions are likely to be less than reported elsewhere due to the size of the water body and influence of wave action. Due to these combined factors, we believe that costs of water saved are likely to be towards the upper end of the range reported rather than the lower. In the worst case, if the model overestimates the reduction in evaporation due to the assumption of monolayer respreading after wave and wind compression, then costs have been underestimated, further testing is required to clarify this. For comparative purposes the cost of water production (without delivery) via desalination at the Gold Coast is estimated to be between \$1.20 and \$1.50/kL (http://www.waterforever.com.au/uploads/67_Desalination.pdf). Based on these numbers it appears that monolayers can save water at a cost competitive with alternative means of augmenting water supplies. Therefore, there is clearly a requirement for further field testing to better define required application rates, the ability of monolayers to respread and actual rates of evaporation reduction. The figures we present here can be considered approximations of expected costs only given current knowledge.

10. SOCIAL IMPACTS

The biggest potential social impact of application of monolayers or surface films to water storages would be the need to restrict recreational uses. Wind and wave action greatly reduce monolayer effectiveness, therefore, use of water craft should be minimised. Unknown changes to water chemistry may also require modification to fishing activities (i.e. increased temperatures could result in blue-green algae blooms). Effects of coming into contact with the monolayer or surface film chemicals appear to be minimal according to manufacturers MSDS sheets.

11. FACTORS AFFECTING EFFICIENCY AND APPLICABILITY

Wind speed is the biggest factor controlling the performance of monolayers. Vines (1962) showed that no evaporation reduction could be detected in their trials of cetyl alcohol monolayers when winds exceeded 24 km/h. Strong winds reduce evaporation savings by blowing the film to the down-wind edge and producing waves to break the layer up. (A discussion on the generation of waves and implication for evaporation reduction by monolayers is given in Appendix B). Obviously the wind characteristics are then going to play an important role in determining whether or not monolayers are a suitable option. Wind direction can also play an important role as this will control the effective fetch of the water body. Also of worthy note is the seasonality of wind speeds. Peak wind speeds during the summer months will further reduce evaporation savings as warmer waters will be exposed during periods of high radiation loading.

The other major factor dictating the successful implementation, or otherwise, of monolayers and surface films is water quality impacts. Any evaporation reducing technique that could interfere with the quality of potable supplies needs to be very carefully evaluated. The risks of making errors are too great to take any chances. This being said a number of water supply agencies around the country have begun utilisation of monolayers on small domestic storages and much could be learnt from their experiences.

12. SUGGESTIONS FOR FURTHER RESEARCH

Further model development and field and laboratory trials should be undertaken to address a number of research questions that have arisen from this desktop study. The research questions to be answered are:

1. What are the monolayer resistance functions for different products? A much better understanding of the resistance imposed by monolayers in different wind conditions is essential. Current estimates use a maximum and a minimum resistance with a straight line fit to these points for conditions in between. Determination of the resistance of available products at different wind speeds would enable more accurate definition of the shape of the resistance function.
2. What is the optimal application rate for different products? Existing evidence suggests that monolayer application rates may need to be up to three times those recommended by manufacturers to achieve satisfactory results. With product costs dominating total application costs (>65% at recommended rates) determination of suitable application rates is essential for accurate economic feasibility assessment.
3. What is the impact of waves on monolayer distribution and how effectively can monolayers respread on large storages? This information is crucial for better understanding of monolayer effectiveness on large storages. This would require development of techniques to detect the coverage of the monolayer. Some potential means are discussed in Barnes (2008) and Saylor et al. (2000).
4. How do real evaporation reductions and water temperatures relate to modelled values? The model predictions of evaporation reduction and water temperature need to be verified with a long term study (at least 1 year). An analysis of the comparative performance of different products would also be useful.

5. What are the impacts of the monolayer and surface film chemicals on water quality? The wide ranging impacts of monolayer application on water quality need to be better understood in a real world situation. Although initial field and laboratory tests suggest that water quality impact from application of monolayers and surface films will be minimal, risks are high when dealing with domestic water supply, therefore extreme caution is required. Studies on the impacts of water quality on reservoir biology will also be required.
6. What are the impacts of the monolayer and surface film chemicals on the water treatment process? For example, how does the chemical product react with treatment membranes, filter media, chlorine, chloramines, fluoride, pH correction products, and alum.
7. What are the health risks and storage and handling issues for monolayer and surface film products? A better understanding of possible health impacts of the product (including by-products) is needed. Long-term risks of exposure need investigation. If aerial spraying is to be used for application, the implications of the drift of chemicals onto people, vegetation, fauna etc. needs to be assessed.
8. What methods are best suited to application of monolayer or surface films over large areas? Can we effectively apply monolayers and surface films to large water bodies? The logistics for large water bodies (>10 km²) will not be insignificant.

13. KEY MESSAGES

- Desktop modelling suggests that over the long-term (1 year) evaporation reductions of about 10% can be expected. This is much less than figures quoted by manufacturers but still represents a significant saving.
- The ability of monolayers to respread following periods of strong wind and wave action is not known. This could be a major controlling factor for the effectiveness of monolayer products when used on storages as large as those in SEQ. Model estimates currently assume that respreading occurs unimpeded after strong winds and waves, this assumption needs verification through field trials.
- The model suggests that field observations of evaporation reduction due to monolayer application can often be misleading because of the short-term nature of these studies (most <3 months). Greater reductions in evaporation are achieved in the first month as the water body moves to a new equilibrium.
- Application of monolayers or surface films does NOT reduce energy inputs into the water storage – with reduced evaporation water temperatures must be expected to rise. Based on our model results water temperature will rise by on average 2.2°C with the greatest effect being in the summer.
- For Wivenhoe Dam at full storage (110 km²) estimated annual evaporation savings are about 17200 ML. This equates to around 4% of the 430,000 ML of water delivered to south-east Queensland on an annual basis (SEQWater 2005 figures).
- Based on a range of typical application rates and changes to evaporation rates it is estimated that monolayers will produce water savings at a cost between \$0.21 and \$1.93 per kL. Further testing will help to better define this range.
- Following termination of monolayer application, increases in evaporation are to be expected due to increased water temperature. This will reduce the overall effectiveness of the monolayer and suggests that application need to be sustained for long periods to be successful.
- Wind speed is the biggest factor influencing monolayer effectiveness. For cetyl alcohol products the effectiveness is reduced to zero at winds exceeding 24 km/h.
- Largest known application is to a water body 10 km². Application to larger water bodies will present a number of logistical challenges.
- Unknown water quality impacts are the biggest risk when applying monolayers or microlayers to potable water supplies.
- Boating activities will disturb the layer reducing effectiveness, therefore, such activities will need to be minimised.

14. REFERENCES

- Alpers, W. and Hühnerfuss, H., 1989. The damping of ocean waves by surface films: a new look at an old problem. *Journal of Geophysical Research*, 94: 6251-6265.
- Barnes, G.T., 1993. Optimum conditions for evaporation control by monolayers. *Journal of Hydrology*, 145: 165-173.
- Barnes, G.T., 2008. The potential for monolayers to reduce the evaporation of water from large water storages. *Agricultural Water Management*, 95(4): 339-353.
- Barnes, G.T. and Gentle, I., 2005. *Interfacial science: an introduction*. Oxford University Press, Oxford, 247 pp.
- Berdie, L., Grimalt, J. and Gjessing, E., 1995. Hydrocarbons, alcohols and sterols in the dissolved + colloidal and particulate phases of the waters from a dystrophic lake, Skjervatjern Lake (Norway). *Water Research*, 29: 2017-2030.
- Blank, M., 1962. The permeability of monolayers to several gases. In: V.K. La Mer (Editor), *Retardation of evaporation by monolayers: Transport processes*. Academic Press, New York, pp. 193-202.
- Boshammer, M., 2007. Aquatrain liquid anti-evaporation film. Independent trial results, Total Ag Services (Dalby) Pty Ltd.
- Bradley, E.F., 1968. A micrometeorological study of velocity profiles and surface drag in the region modified by a change in surface roughness. *Quarterly Journal of the Royal Meteorological Society* 94: 361-379.
- Bureau of Reclamation, 1962. Water-loss investigations: Lake Cachuma - 1961 evaporation reduction investigations. Chemical Engineering Laboratory report no, SI-33, US Bureau of Reclamation, Denver.
- Calder, I.R. and Neal, C., 1984. Evaporation from saline lakes: a combination equation approach. *Hydrological Sciences Journal*, 29(1): 89-97.
- Chang, S., McClanahan, M. and Kabler, P., 1962. Effect of bacterial decomposition of hexadecanol and octadecanol in monolayer films on the suppression of evaporation loss of water. In: V.K. La Mer (Editor), *Retardation of Evaporation by Monolayers: Transport Processes*. Academic Press, New York, pp. 119-131.
- Committee of Collaborators, 1959. Water-loss investigations: Lake Hefner 1958 evaporation reduction investigations, U.S. Bureau of Reclamation.
- Cox, C.S., 1958. Measurement of slopes of high-frequency waves. *Journal of Marine Research*, 16: 199-225.
- Craig, I., Green, A., Scobie, M. and Schmidt, E., 2005. *Controlling Evaporation Loss from Water Storages*. National Centre for Engineering in Agriculture Publication 1000580/1, USQ, Toowoomba.
- Crow, F.R., 1963. The effect of wind on evaporation suppressing films and methods of modification, *International union of Geodesy and Geophysics. International association of scientific hydrology. General Assembly of Berkeley*, pp. 26-37.
- Csanady, G.T., 2001. *Air-sea Interaction: Laws and Mechanisms*. Cambridge University Press, Cambridge.
- Davies, J.T. and Vose, R.W., 1965. On the damping of capillary waves by surface films. *Proceedings of the Royal Society of London Series A*, 286: 218-234.
- de Bruin, H.A.R., 1982. Temperature and energy balance of a water reservoir determined from standard weather data of a land station. *Journal of Hydrology*, 59: 261-274.
- Dove, H. and Mayes, R., 1991. The use of plant wax alkanes as marker substances in studies of the nutrition of herbivores: A review. *Australian Journal of Agricultural Research*, 42: 913-952.
- Downing, A.L. and Melbourne, K.V., 1957. Chemical conservation of water. *Journal of the Institute of Water Engineering*, 11(5): 438-442.
- Edinger, J.E., Duttweiler, D.W. and Geyer, J.C., 1968. The response of water temperature to meteorological conditions. *Water Resources Research*, 4: 1137-1143.
- Fitzgerald, L.M. and Vines, R.G., 1963. Retardation of evaporation by monolayers: practical aspects of the treatment of large water storages. *Australian Journal of Applied Science*, 14: 340-346.
- Franzini, J.B., 1961. Progress report-evaporation suppression research. *Journal of Geophysical Research*, 66(8): 2529-&.
- Giblett, M.A., 1921. Some problems connected with evaporation from large expanses of water. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 99(701): 472-490.

- Gladyshev, M., 2002. *Biophysics of the Surface Microlayer of Aquatic Ecosystems*. IWA Publishing, London, United Kingdom.
- Goldacre, R., 1949. Surface films on natural bodies of water. *Journal of Animal Ecology*, 18(1): 36-39.
- Grundy, F., 1957a. Reduction of evaporation from reservoirs, *Proceedings of the 2nd International Congress of Surface Activity*, London, pp. 270-274.
- Grundy, F., 1957b. The use of cetyl alcohol to reduce evaporation. *Journal of the Institute of Water Engineering*, 11(5): 429-439.
- Grundy, F., 1958. The use of cetyl alcohol in solution to reduce evaporation from reservoirs. Report on an experiment on Malya Reservoir in Tanganyika Territory in August 1957. *Memoirs of the East African Meteorological Department*, 2(11): 1-11.
- Harbeck, G.E. and Koberg, G.E., 1959. A method of evaluating the effect of a monomolecular film in suppressing reservoir evaporation. *Journal of Geophysical Research*, 64(1): 89-93.
- Hawke, J.G. and Alexander, A.E., 1960. The influence of surface active compounds upon the diffusion of gases across the air-water interface, 3rd International Congress of Surface Activity, Cologne, pp. 184-188.
- Hayes, M.L., 1959. Biological effects of hexadecanol used to suppress water evaporation from reservoirs, Fort Collins Colorado, Colorado State University.
- Jeffrey, S.J., Carter, J.O., Moodie, K.B. and Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software with Environment Data News*, 16(4): 309-330.
- Keijman, J.Q. and Koopmans, R.W.R., 1973. A comparison of several methods of estimating evaporation of Lake Flevo, *Hydrology of lakes*. IAHS publication no 109, Helsinki, pp. 225-232.
- Kinsman, B., 1965. *Wind Waves: Their Generation and Propagation on the Ocean Surface*. Prentice-Hall, Englewood Cliffs, NJ.
- La Mer, V.K., 1962. Retardation of evaporation by monolayers: transport processes. Academic Press, New York, xx, 277 p. pp.
- Lighthill, M.J., 1962. Physical interpretation of the mathematical theory of wave generation by wind. *Journal of Fluid Mechanics*, 14: 385-398.
- Liu, Y. and Wu, J., 2006. Use of n-hexadecane as an oxygen vector to improve *Phaffia rhodozyma* growth and carotenoid production in shake-flask cultures. *Journal of Applied Microbiology*, 101: 1033-1038.
- MacRitchie, F., 1968. Role of monolayers in retardation of evaporation. *Nature*, 218: 669-670.
- MacRitchie, F., 1969. Evaporation retarded by monolayers. *Science*, 163(3870): 929-931.
- Mansfield, W.W., 1972. Evaporation retardation by monolayers. *Science*, 176: 944.
- Matthews, G.D., 1959. Review of Lake Hefner Results, Water-loss investigations: Lake Hefner studies. U.S. Bureau of Reclamation, pp. 85 pp.
- McArthur, J.K.H., 1960. Fatty alcohols for water conservation, *Proceedings of the 3rd International Congress of Surface Activity*, Mainz, pp. 595-598.
- McJannet, D.L., Webster, I.T. and Cook, F.J., 2008a. An evaporation wind function for open water bodies of variable size. *Water Resources Research*, Submitted.
- McJannet, D.L., Webster, I.T., Stenson, M. and Sherman, B., 2008b. A method to estimate open water evaporation losses across the Murray Darling Basin. CSIRO Science Report.
- Miles, J.W., 1957. On the generation of surface waves by shear flows. *Journal of Fluid Mechanics* 3: 185-204.
- Miles, J.W., 1959. On the generation of surface waves by shear flows, 2. *Journal of Fluid Mechanics* 6: 568-582.
- Monteith, J.L., 1965. Evaporation and the environment. In: G.E. Fogg (Editor), *The state and movement of water in living organisms*. Cambridge University Press, London.
- Munster, U., Heikkinen, E. and Knulst, J., 1998. Nutrient composition, microbial biomass and activity at the air-water interface of small boreal forest lakes. *Hydrobiologia*, 363: 261-270.
- Mysels, K.J., 1972. Evaporation retardation by monolayers. *Science*, 176: 944-945.
- Navon, U. and Fenn, J.B., 1971a. Interfacial mass and heat transfer during evaporation: I. An experimental technique and some results with a clean water surface. *AIChE*, 17(1): 131-136.
- Navon, U. and Fenn, J.B., 1971b. Interfacial mass and heat transfer during evaporation: II. Effect of monomolecular films on natural convection in water.
- Norkrans, B., 1980. Surface microlayers in aquatic environments. *Advances in Microbial Ecology*, 4: 51-85.
- Phillips, O.M., 1957. On the generation of surface waves by turbulent wind. *Journal of Fluid Mechanics*, 2: 417-445.
- Phillips, O.M., 1977. *The Dynamics of the Upper Ocean*. Cambridge University Press, New York.

- Roberts, W.J., 1962. Reducing water vapor transport with monolayers. In: V.K. La Mer (Editor), Retardation of evaporation by monolayers: Transport processes. Academic Press, New York, pp. 193-202.
- Sartori, E., 2000. A critical review on equations employed for the calculation of the evaporation rate from free water surfaces. *Solar Energy*, 68(1): 77-89.
- Saylor, J.R., Smith, G.B. and Flack, K.A., 2000. Infrared imaging of the surface temperature field of water during film spreading. *Physics of Fluids*, 12(3): 597-602.
- Silvey, J.K.G., 1960. Physical, chemical and biological effects of hexadecanol on Lake Hefner. *Journal American Water Works Association*, 52(6): 791-802.
- Sutherland, K.L., 1957. Economic methods of controlling evaporation of water. *Research (Science and its application to industry)* 10(5): 198-204.
- Timblin, L.O., 1957. Preliminary toxicity studies with hexadecanol reservoir evaporation reduction. Chemical Engineering Laboratory Report No. SI-10, U.S. Bureau of Reclamation.
- Uthoff, S., Stoveken, T., Weber, N., K., V., Klein, E., Kalscheuer, R. and Steinbuchel, A., 2005. Thio wax ester biosynthesis utilizing the unspecific bifunctional wax ester synthase/acyl coenzyme A:Diacylglycerol Acyltransferase of *Acinetobacter* sp Strain ADP1. *Applied and Environmental Microbiology*, 71(2): 790-796.
- van de Graaff, R.H.M., 2007. Aquatrain anti-evaporation film. Independent water quality report, van de Graaff & Associates Pty Ltd.
- Vines, R.G., 1962. Evaporation control: A method of treating large water storages. In: V.K. La Mer (Editor), Retardation of evaporation by monolayers: Transport processes. Academic Press, New York, pp. 193-202.
- Walter, J., 1963. The use of monomolecular films to reduce evaporation, International union of Geodesy and Geophysics. International association of scientific hydrology. General Assembly of Berkeley, pp. 39-48.
- WaterSavr, 2006. Coliban water evaporation reduction trial using WaterSavr.
- Webster, I.T. and Hutchinson, P.A., 1994. Effect of wind on the distribution of phytoplankton cells in lakes revisited. *Limnology and Oceanography*, 39(2): 365-373.
- Weisman, R.N. and Brutsaert, W., 1974. Evaporation and cooling of a lake under unstable atmospheric conditions. *Water Resources Research*, 9: 1242-1257.
- Wixson, B.G., 1966. Studies on the ecological impacts of evaporation retardation monolayers. TR-6, Texas Water Resources Institute, Texas A & M University, Texas.
- Wolbeer, H.J., 1963. The calculated efficiency of monolayers in relation to increased water temperature, International union of Geodesy and Geophysics. International association of scientific hydrology. General Assembly of Berkeley, pp. 13-23.
- Wu, J., 1971. Evaporation retardation by monolayers: Another mechanism. *Science*, 174: 283-285.

APPENDIX A

Monolayer costing - Distributed Applicators

	Recommended	3 x Recommended	Units	Notes
Evaporation savings				
Dam area	75	75	km ²	Average for last 14 years
Evaporation savings	95 mm – 310 mm	95 mm – 310 mm	mm/y	Due to monolayer
Evaporation savings	6% - 20%	6% - 20%	%	
Volume savings	7125 - 23250	7125 - 23250	ML/y	
Product				
WaterSavr reapplication	1	1	days	
Applications	120	120	/y	Summer only
Application rate	35	105	kg/km ²	
Weight required	315000	945000	kg/y	
Product cost	\$10.00	\$10.00	\$/kg	
Total product cost	\$ 3,150,000.00	\$ 9,450,000.00	\$/y	
Application				
Applicator	\$ 2,000.00	\$ 2,000.00	\$/unit	
Area covered by unit	0.2	0.2	km ²	
Units required	500	500		Enough to cover at full storage
Cost of units	\$ 1,000,000.00	\$ 1,000,000.00	\$	
Installation costs	\$ 5,000.00	\$ 5,000.00	\$/unit	
Total installation costs	\$ 2,500,000.00	\$ 2,500,000.00	\$	
Installation and unit cost	\$ 3,500,000.00	\$ 3,500,000.00	\$	
Life of unit	10	10	y	
Applicator costs	\$ 350,000.00	\$ 350,000.00	\$/y	
Unit maintenance costs	\$ 500.00	\$ 500.00	\$/unit/y	
Total maintenance costs	\$ 250,000.00	\$ 250,000.00	\$	
Total application cost	\$ 600,000.00	\$ 600,000.00	\$/y	
Storage				
Storage shed facilities	\$ 450,000.00	\$ 600,000.00	\$/unit	Assume \$500 / m ²
Number of storages	20	20		25 applicators per shed
Cost of storages	\$ 9,000,000.00	\$ 12,000,000.00		
Life of storage	40	40	y	
Storage shed costs	\$ 225,000.00	\$ 300,000.00	\$/y	
Land per storage	2.5	3	ha	0.5 ha (1x) / 1ha (3x) + 2 ha rd
Land Cost	\$ 7,000.00	\$ 7,000.00	\$/ha	
Total land cost	\$ 350,000.00	\$ 420,000.00	\$	
Land capital write-off period	40	40	y	Tax write off period (ATO)
Land cost	\$ 8,750.00	\$ 10,500.00	\$/y	
Access road distance	2	2	km	
Total road distance	40	40	km	
Access road costs	\$ 100,000.00	\$ 100,000.00	\$/km	
Road lifespan	15	15	y	
Total rd cost	\$ 266,666.67	\$ 266,666.67	\$/y	
Forklift	\$ 10,000.00	\$ 10,000.00	\$/unit	
Forklift costs	\$ 200,000.00	\$ 200,000.00	\$	One per shed

Forklift Lifespan	10	10	y
Total forklift costs	\$ 20,000.00	\$ 20,000.00	\$/y
Storage maintenance/signage	\$ 5,000.00	\$ 5,000.00	\$/y/storage
Storage maintenance/signage	\$ 100,000.00	\$ 100,000.00	\$/y
Total storage cost	\$ 525,416.67	\$ 602,166.67	\$/y

Boat

Boat cost	\$ 50,000.00	\$ 50,000.00	\$	
Applicators serviced per team	20	20	\$/d	
Product reload period	9	3	d	Max. capacity 60 kg
Applicators requiring visits	58	175	/d	
Teams/boats required	3.0	9.0		
Boat life	20	20	y	
Total boat cost	\$ 7,500.00	\$ 22,500.00	\$/y	
Maintenance	\$ 2,500.00	\$ 2,500.00	\$/boat/y	
Total boat maintenance	\$ 7,500.00	\$ 22,500.00	\$/y	
Boat fuel	40	40	l/d/boat	
Fuel cost	\$ 1.50	\$ 1.50	\$	
Total fuel cost	\$ 21,600.00	\$ 64,800.00	\$/y	
Storage bins	\$ 1,000.00	\$ 1,000.00	\$/boat/y	
Total bin costs	\$ 3,000.00	\$ 9,000.00	\$	
Boat storage	\$ 5,000.00	\$ 5,000.00	\$/y/boat	
Total boat storage	\$ 15,000.00	\$ 45,000.00	\$	
Fuel storage facilities	\$ 1,000.00	\$ 1,000.00	\$/y/boat	
Total Fuel storage costs	\$ 3,000.00	\$ 9,000.00	\$/y	
Total boat costs	\$ 57,600.00	\$ 172,800.00		

Transport

Distance travelled	175	175	km/d/team
Total Distance travelled	63000	189000	\$/y
km cost	\$ 2.00	\$ 2.00	\$/km
Total Transport cost	\$ 126,000.00	\$ 378,000.00	\$/y

Salary/office costs

Full time staff required	12	36		Four per team
Annual salary	\$ 40,000.00	\$ 40,000.00	\$/y	
Salary multiplier	2.1	2.1		
Total salary	\$ 331,397.26	\$ 994,191.78	\$/y (120days)	
Office space costs	\$ 7,000.00	\$ 7,000.00	\$/person/y	
Total office costs	\$ 84,000.00	\$ 252,000.00	\$	
Approvals	\$ 1,000.00	\$ 1,000.00	\$/year	
Total salary/office costs	\$ 416,397.26	\$ 1,247,191.78	\$	

TOTAL COST **\$ 4,875,413.93** **\$ 12,450,158.45** **\$/y**

COST OF WATER SAVED **\$0.21 - \$0.68** **\$0.54- \$1.75** **\$/KL**

Monolayer costing - Aerial Application

	Recommended	3 x Recommended	Units	Notes
Evaporation savings				
Dam area	75	75	km ²	Average for last 14 years
Evaporation savings	95 mm – 310 mm	95 mm – 310 mm	mm/y	Due to monolayer
Evaporation savings	6% - 20%	6% - 20%	%	
Volume savings	7125 - 23250	7215 - 23250	ML/y	
Product				
WaterSavr reapplication	1	1	days	
Applications	120	120	/y	Summer only
Application rate	35	105	kg/km ²	
Weight required	315000	945000	kg/y	
Product cost	\$10.00	\$10.00	\$/kg	
Total product cost	\$ 3,150,000.00	\$ 9,450,000.00	\$/y	
Application				
Plane capacity	1,500	1,500	kg	
Coverage per load	42.9	14.3	km ²	
Area covered	4	4	km ² /h	
Loads required	2	5		Return to airfield for reload
Travel time	2	5	h	
Time for total cover	18.75	18.75	h	
Spray time plus travel time	20.75	23.75	h	
Contractor rate	\$1,400.00	\$1,400.00	\$/h	Approximate
Spray cost	\$29,050.00	\$33,250.00	\$/d	
Total application cost	\$ 3,486,000.00	\$ 3,990,000.00	\$/y	
Storage				
Storage shed facilities	\$ 250,000.00	\$ 250,000.00	\$/unit	Storage at airport
Forklift	\$ 10,000.00	\$ 10,000.00	\$/unit	
Forklift Lifespan	10	10	y	
Total forklift costs	\$ 1,000.00	\$ 1,000.00	\$/y	
Storage maintenance/signage	\$ 5,000.00	\$ 5,000.00	\$/y/storage	
Total storage cost	\$ 256,000.00	\$ 256,000.00	\$/y	
Salary/office costs				
Full time staff required	1	1		Four per team
Annual salary	\$ 40,000.00	\$ 40,000.00	\$/y	
Salary multiplier	2.1	2.1		
Total salary	\$ 27,616.44	\$ 27,616.44	\$/y (120days)	
Office space costs	\$ 10,000.00	\$ 10,000.00	\$/person/y	
Approvals	\$ 1,000.00	\$ 1,000.00	\$/year	
Total salary/office costs	\$ 38,616.44	\$ 38,616.44	\$	
TOTAL COST	\$ 6,930,616.44	\$ 13,734,616.44	\$/y	
COST OF WATER SAVED	\$0.30 - \$0.97	\$0.59- \$1.93	\$/KL	

APPENDIX B

How wind generates water waves, and the implications for evaporation reduction by monolayers

In order to understand how a wind blowing across the water surface reduces the effectiveness of a monolayer in reducing evaporation, it is necessary to take account of the drag force across the water surface. It is this shear or drag force which causes the wind to generate water waves, known as “wind waves”. See for example Lighthill (1962), Kinsman (1965), Phillips (1977) or Csanady (2001). Although the general principles are well known, the details of how energy is transferred from turbulent wind to water waves are not fully understood.

When a turbulent wind blows across an initially calm water surface, the first waves to appear at a wind speed of about 0.25 to 1 m s⁻¹ are the capillary waves. The restoring force to move from capillary waves to a calm water surface is the surface tension. The surface capillary waves initially grow in height at a linear rate proportional to the wind speed, as explained by Miles (1957; 1959). It has long been observed that a surface film has the effect of damping the capillary waves (Davies and Vose, 1965), and it is believed that a portion of the wave energy loss is due to a viscous drag of the associated chains of water molecules which are bonded to the molecules of the adsorbed surface film. The drag occurs when the molecules are forced into movement as a result of the alternating compression and expansions of the surface caused by the passing progressive waves. The circular motions of the water particles laterally compress the surface film on the forward side of the wave, and expand it at the rear. The surface tension forces oppose this, and try to move the surface in the opposite direction to the water motion, which is called the Marangoni effect.

Once these small waves have formed due to the effects of the turbulent wind, they start to interact with the atmosphere through pressure differences and through the increased water surface roughness, which makes the velocity field in the air more complicated and more turbulent. This increases the effective eddy diffusivity of water vapour above the water surface, increasing mixing and increasing the flux of water vapour away from the surface.

If the wind continues to blow, the waves grow in size until they have a length of about 1.7 cm and a travel at a speed of about 0.24 m sec⁻¹; if they grow longer than this they start to become gravity waves for which the restoring force is mainly gravitational. Turbulent eddies in the air cause “cat’s paws” which are groups of capillary-gravity waves of about 40 cm across, which indicate areas of locally high shear stress. At wind speeds above about 2 m s⁻¹ gravity waves are formed, and these waves grow at rates exponentially proportional to the wind speed (as explained by Phillips (1957)), producing larger and larger waves. However, the transfer of energy from capillary to longer gravity waves is reduced by the presence of the surface film. This was first observed by Cox (1958) and has since been studied by many authors, see for example Alpers and Hühnerfuss (1989).

At higher wind speeds, there are irregular sharp crests with poorly defined speeds and directions, which further increases the effective eddy diffusivity of the water vapour and its vertical flux rate.

The local rapid motion of the water surface and the variations in wind shear on different parts of the wave can also cause the surface film to develop inhomogeneities, which decreases its ability to reduce evaporation. When the wind is blowing from land across a water body the waves are short, of small amplitude and low speed. The waves further from the upwind shore become longer and higher and more regular until they reach the downwind edge of the water body. The sizes and speeds of the waves depend on the length of the fetch and the depth of the water body, the waves being smaller and slower on shallower water. Also, the waves may be damped by growths of water weed at or near the surface. The wind shear acting in one consistent direction for a long time also causes the surface film to be pushed towards the downwind shore, leaving a gap upwind. If the waves are breaking on a sloping beach at the downwind shore then the surface film may be deposited on the beach by breaking waves, and when the water sinks into the porous beach some of the surface film may adhere to the particles and be temporarily or permanently lost to the water body.

At higher wind speeds the air and water velocity fields interact in a complicated way and there is air flow separation downwind from the wave crests, with reversal of air flow on the downwind sides of the waves. The waves break and form white caps and water drops form as spray at the top of the wave. The evaporation of these small drops greatly increases the overall evaporation rate, and the surface film will have little effect on this.

The surface layer reduces evaporation by forming a physical barrier to the movement of vapour, and also to some extent by reducing the size of the water waves which tend to cause more turbulence and to disrupt the surface layer. Both of these processes are eventually negated by a sufficiently high wind acting for a sufficiently long time, but the degree of the reduction depends on the size of the fetch and the depth of the water body.

This review shows that the effectiveness of monolayers is greatly limited by wind and wave action which, for a given water body, is usually related to its size or fetch. With this in mind we should expect lower evaporation reductions from monolayer use on storages in SEQ than those reported in the literature because the SEQ storages are much bigger than any water body tested before.

Urban Water Security Research Alliance

