‘SMART’ MONOLAYER APPLICATION AND MANAGEMENT TO REDUCE EVAPORATION ON FARM DAMS – FORMULATION OF A UNIVERSAL DESIGN FRAMEWORK

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Abstract: Recent analyses of the utility of chemical monolayers to reduce the evaporation from extensive open water surfaces have shown them to be a potentially economical, low-impact and environmentally benign. However, monolayer performance is highly variable due to site and environmental factors, principally dam size, climate, microclimate, and interactions with natural water microlayers, factors which vary over time and between dams and dam sites. These differences influence both the design of an appropriate monolayer application system and the management of the system in response to prevailing conditions and/or user requirements.

This paper reviews the physical and biological factors which must be accommodated and introduces a Universal Design Framework for optimal monolayer application. The framework seeks to inform the selection of monolayer compound and appropriate equipment, including the design and number of applicators, their arrangement on-site and application strategies for a given dam site; and also to ensure sustained autonomous operation is efficient, both as regards evaporation reduction and monolayer use.

Progress is also reported towards the design of an autonomous electromechanical system for the optimal application and spreading of monolayer.
Introduction

Evaporation and Evaporation Mitigation

Annual evaporation losses from farm water storages in Australia can potentially exceed 40% of storage volume (Craig et al. 2005a). Baillie (2008) estimates evaporation losses from on farm storages in Australia to be in the range of 1,320GL to 2,880GL (depending on volume in storage, evaporation potential and storage characteristics). In addition, considerable water distribution losses are present in irrigation channels due to evaporation and seepage (Baillie et al. 2007). As a consequence, agricultural production opportunities worth tens of millions of dollars evaporate with the water.

Evaporation losses can be minimised to some extent through the design of deep, small surface area storages or construction of storages with cells (Baillie et al. 2007). Also the use of wind barriers, shelter belts and even dam destratification can help to reduce evaporative loss. Commercial products such as physical covers, suspended shade structures, modular floating objects and chemical monolayers are also available, and have been evaluated by the National Centre for Engineering in Agriculture (NCEA) with respect to performance and breakeven cost (Craig et al. 2005b).

Craig et al. (2005b) concluded that high evaporation savings are possible if physical covers are used on small farm dams less than 10ha in size. Physical covers can also be used on larger dams, but they are generally uneconomic due to the high capital investment required. In contrast, economic analyses indicate that for larger dams chemical monolayers represent potentially the best option for conserving agricultural water in Australia, despite being less effective than physical structures (10-40% evaporative reduction compared with up to 90% for physical structures). However, the poor performance of currently available monolayer products highlights deficiencies in their physical and environmental durability, and in the available application methods. The results of recent research at the NCEA indicate the potential for significant improvements in both the monolayer product, and in the application technology (Craig et al. 2007).

Monolayer and Microlayer Performance Characteristics

Monolayers are chemical films one molecule thick (~2nm) formed at a phase boundary such as the water surface (Gaines 1966; Barnes and Gentle 2005). These molecules are amphiphilic as each has a hydrophilic base and a hydrophobic stem. The most commonly used monolayer materials for evaporation mitigation are long-chain fatty alcohols such as hexadecanol (C\textsubscript{16}) and octadecanol (C\textsubscript{18}), which spontaneously self-spread upon contact with water (Barnes 2008). Long-chain fatty alcohols with carbon lengths of up to 16 are common components of plant waxes and microbial storage lipids, explaining why artificial monolayers such as hexadecanol are completely biodegraded within 1-4 days after application to natural water storages (Dove and Mayes 1991).

Waxy leaf and bark litter entering natural water bodies are degraded by microbial and photochemical processes to from a natural surface film or microlayer (Bunn 1986). The physical similarity between natural microlayers and fatty alcohol monolayers may contribute to the poor performance of currently available monolayer compounds in reducing evaporative loss (Norkrans 1980; Gladyshev 2002). Recent studies have revealed that microlayers may degrade the structure of monolayers by disrupting the orderly molecular packing required to reduce evaporative loss.

Monolayer compounds need to be in a condensed state (tightly packed molecules) to achieve a surface pressure of greater than 30mN/m consistently across the water surface, to effectively reduce evaporative loss (Barnes 2008, Table 1a). Microlayer surface pressures on open water are usually well below this (less than 6mN/m, Table 1b), indicating that their chemical composition may be too heterogeneous to provide the tight packing required to be effective (Norkrans 1980). Microlayer composition varies on different water storages, indicating that a range of improved monolayer
compounds may be required. However, physical factors such as wind speed also disrupt artificial monolayers, indicating that there may be times when applying monolayers may not be effective.

During early field studies at Lake Hefner in the United States, researchers found wind to be the single most important factor in the application and maintenance of monolayer film (Fietz 1959). The deleterious effect of wind on a monolayer film is twofold; firstly wind displaces the film on the downwind shore, and secondly wind creates waves which can break-up the film (Fitzgerald and Vine 1963; Frenkiel 1965; Crow 1961 and 1963; Reiser 1969). Through both these wind induced effects, monolayer film coverage across the water surface is effectively reduced. Recent studies have indicated that monolayer compounds of the C\textsubscript{16} variety are easily affected by relatively low wind velocities of around 5 to 7 km/h (McMahon et al. 2008).

Methods to apply monolayer products to open water surfaces under natural conditions were first developed some 53 years ago (Mansfield 1955). Since then a plethora of methods for applying a monolayer have followed such as Vines (1958 and 1960), Treloar and Dunstan (1959), Crow (1963), Walter (1963), Cliff and Resnick (1964), Florey (1965), Nicholsonchuk and Pohjakas (1967), Reiser (1969), Koberg (1969), Dressler & Guinat (1973), and Lahav and Alto (1984). Many of these application methods are depended on simple, mechanical devices that at most only ever accounted for wind direction and/or wind speed. Labour requirements were also high, reducing the feasibility of repeat application in the short term. As a result, very few monolayer based evaporation mitigation systems were ever commercialised.

**Research Need**

To improve monolayer performance, new more environmentally resilient compounds must be developed, in combination with improved application and decision support systems. Research on the effect of water quality and climatic factors on the performance of different monolayer compounds is providing a more objective framework to match specific products to specific sites. To utilise this information a **Universal Design Framework (UDF)** must be developed to inform the design of a monolayer application system for a specific site. The UDF will inform the operational procedures (the implementation of a unique application strategy for a specific product), for the specified site on a daily basis.

The work necessary to establish this UDF determines the research requirements for the design, development and evaluation of ‘smart’ autonomous systems for the optimal application of chemical monolayer to open water surfaces. A real-time control methodology which utilises both on-site data (real time) and remote data (forecast) to improve the accuracy and effectiveness of monolayer

<table>
<thead>
<tr>
<th>Monolayer Compound</th>
<th>Monolayer Surface Pressure</th>
<th>Water Storage</th>
<th>Catchment Description</th>
<th>Microlayer Surface Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexadecanol (C\textsubscript{16})</td>
<td>39 mN/m</td>
<td>Windolff Dam (Caffey)</td>
<td>Bore water</td>
<td>&lt; 5.9 mN/m</td>
</tr>
<tr>
<td>Octadecanol (C\textsubscript{18})</td>
<td>35 mN/m</td>
<td>Brimblecombe ring tank, Forrest Hill</td>
<td>Peak flow off-take from Sandy Creek, and bore water</td>
<td>&lt; 5.9 mN/m</td>
</tr>
<tr>
<td>Docosanol (C\textsubscript{22})</td>
<td>40 mN/m</td>
<td>Narda Lagoon, Laidley</td>
<td>Overland flow from rural residential land and a sawmill</td>
<td>5.9 mN/m</td>
</tr>
</tbody>
</table>
application, will need to be developed. The methodology will be realised in the form of a real-time decision-making system.

**Development of the UDF**

The candidate UDF comprises a set of algorithms based on site-specific data provided by the user (dam owner). The UDFs six steps, as currently organised, are set out below:

**Step 1 - Water storage scale**: Surface area and shape of the farm water storage during peak evaporation period (usually October – March for the Southern Hemisphere) or critically required (user-defined) application period is entered by the user.

**Step 2 - Topography and microclimate (local)**: The key features to be determined are water storage type, average water depth, exposure to wind, and orientation of dam including four geographical co-ordinate points and/or maximum and minimum fetch across the water surface, Figure 1.

**Step 3 - Climate (meteorological data)**: A climatic data analysis is required of monthly average evaporation rate, monthly average rainfall, monthly average air temperature, wind speed frequency analysis and prevailing wind direction, Figure 2.

<table>
<thead>
<tr>
<th>Dam design:</th>
<th>Gully dam</th>
<th>Ringtank</th>
<th>Irregular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average depth:</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>0m - 1.9m</td>
<td>2m - 3.8m</td>
<td>&gt; 4m</td>
<td></td>
</tr>
<tr>
<td>Wind exposure:</td>
<td>Low sheltered</td>
<td>Medium partially sheltered</td>
<td>High exposed</td>
</tr>
<tr>
<td>Orientation of dam:</td>
<td>g= first geographical co-ordinate (GPS): Latitude= Longitude=</td>
<td>g= second geographical co-ordinate (GPS): Latitude= Longitude=</td>
<td>g= third geographical co-ordinate (GPS): Latitude= Longitude=</td>
</tr>
<tr>
<td></td>
<td>OR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a= angle of major axis from North - South line:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d=max= distance of maximum (major axis) fetch across water surface:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d=average distance perpendicular to major axis:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 1. UDF – Step 2 defines topography and microclimate.*
Step 3 defines the (regional) climatic conditions.

Step 4 - Water quality and biological factors: Key features to be determined are catchment vegetation, catchment area, water colour, turbidity and water chemistry (pH, electrical conductivity and UV absorbents, Figure 3.)
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**Step 5 - Monolayer product choice:** It is envisaged that a suite of monolayer compounds will be available to choose from according to firstly the environmental characteristics of a particular water body then the climatic and topographical features of that site, Figure 4.

**Step 6 - Water value:** The value of the water would be influenced by two factors, the actual cost of the water and the value of the crop that water is being used to irrigate. At present it is envisaged that classification into one of three categories, low ($0 - $299/ML), medium ($300 - $999/ML) and high (> $1,000/ML) will suffice.

**Methodology**

The candidate UDF has been conceived as a methodology for informing monolayer system design for any given site. The UDF will be used for determining necessary monolayer application equipment, including number of applicators, their arrangement and application strategies for a given dam site and monolayer product. The UDF will also influence the operational procedures (implementation of application strategies) for the site on a daily basis.

The first step is to collect the required data for each of the inputs in the UDF. The data would be collected and used in the following way: (i) Data required for steps 1 and 2 of the UDF can all be determined by a basic on-site analysis. Step 4 can also be completed during the on-site analysis by determining catchment area and vegetation, density of native trees, water colour and turbidity, and either via on-site measurements of water for quality testing or via a nearby laboratory to determine pH, electrical conductivity and UV absorbents. All inputs required for step 3 could be determined remotely.
using a combination of Bureau of Meteorology (BOM) and SILO historical meteorologic data. All BOM and SILO data are readily available over the internet.

For step 5, monolayer product choice is ultimately a user based decision guided by the decision matrix provided of products available and their individual characteristics, firstly with respect to water quality and biological factors, and then with respect to climatic factors. The user then matches their water storage characteristics with the examples provided to select suitable monolayer product/s. The decision matrix is provided as a tool to guide the user in selecting a suitable monolayer product/s, not to make the choice for them. For step 6 the '$' value of the water to be protected will vary from location to location and at different times with respect to crop growth and would be a user determined input. Information is also provided by the user concerning critical periods during the year when water is most needed to be protected.

(ii) The information provided in each of the steps in the UDF is then used in determining the necessary application equipment, including number of applicators and their arrangement on site. The information from the UDF required for determining this is surface area, shape and orientation of the water storage, including the percentage of prevailing wind direction.

(iii) The information provided in the UDF influences the operational procedures (implementation of application strategies) for a particular site. The required operational information is average potential evaporation rate, current and forecast, water value and critical time when the water is most needed which informs when it is best/economically viable to apply monolayer. The selected monolayer product informs application rate and expect half-life/breakdown. Again, basic information about the dam shape, surface area, orientation and applicator location will inform application strategies and more specifically, spatial varied application demand. Information about the orientation of major and minor axes of the water surface with respect to wind direction and average depth will inform expected wave heights.

Although the relevant information from the UDF influences application strategies for a particular site, the daily application demand will vary according to on-site climatic data. This is provided by an Automatic Weather Station (AWS) in conjunction with the dam Seepage and Evaporation Measurement Technique (SEMT) developed by the present group (reported in Craig 2006).

**Prototype ‘Smart’ Application System**

Although an appropriate applicator design is still currently under development, progress is reported towards the design of a prototype ‘smart’ autonomous system for the optimal application of chemical monolayer to open water surfaces. Including the development of a decision-making system capable of individually and adaptively controlling the monolayer dosage rate for each applicator according to spatial distribution of monolayer coverage, meteorological conditions on-site and forecast, evaporation rate of water, and volatilisation of monolayer.

The design requirements for the ‘smart’ application system, as influenced by the UDF, are as follows:

(i) **Sensors** are required for accurately measuring and monitoring (on-site) changing environmental conditions that influence monolayer performance, such as:

- evaporation
- seepage (loss of water through the bottom and sides of the dam)
- air temperature
- wind speed and direction
- solar radiation
- relative humidity
- rainfall

(ii) Due to the natural biodegradation of monolayer, re-application is a must every 2-4 days (with currently-available materials). Hence **autonomous application** of monolayer is required including continuous or intermittent application of varying dosage amounts as appropriate.
The application demand to maintain an effective cover of monolayer on a farm water body will constantly be changing as influenced by on-site environmental conditions. Therefore, rate and frequency of monolayer application will need to be autonomously calculated in real-time by a **coordinator**. This system will need to be capable of conducting a number of tasks, primarily, the analysis of input data from sensors, applying algorithm/s to that data and decision support rules to calculate application/re-application rate for monolayer.

The sensors, coordinator and applicator all communicate wirelessly between each other. Data is sent from the AWS and SEMT to the coordinator for analysis. Once the coordinator has calculated the required application rate this information is sent to the applicators to action. To cover the entire surface of a farm dam with monolayer a number of applicators will be required, most likely a combination of shore based and floating applicators (as determined by the UDF). According to literature, monolayer in a liquid form is far easier to store, handle, distribute and apply than monolayer in a solid form. There is also a large amount of off-the-shelf hardware available for liquid transfer. For this reason the applicator was designed for the application of monolayer in a liquid form.

The dosing decisions would be determined by a simple set of hierarchical rules in the form of an algorithm/s for real-time calculation of optimal dosage rate. The rules would be structured as detailed in Figure 5. Unfortunately details of the logic of Figure 5 are beyond the space available in this paper.

![Figure 5. Decision support rules flow diagram.](image)

**Findings and Conclusions to Date**

The UDF and ‘smart’ application system are both at a stage of relative infancy, hence operational results are limited. However, due to the large variability in monolayer product performance, influenced by a number of site-specific environmental conditions and user requirements, there is no ‘one-size-fits-all’ monolayer product, application system or application strategy. Therefore, a UDF has been formulated to assist farm dam owners and managers, who are interested in utilising a monolayer-based evaporation mitigation system. It is envisaged that the UDF will form the basis of a publicly available software tool.

**Recommendations**

Further development and evaluation of the UDF is planned through the results from further investigations into:
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- Applicator design/s and the development of a computer simulation for determining an optimal number of applicators and their arrangement for a nominated site and spatial scale.
- Biological/microlayer interaction including the characterisation of the properties of these compounds to inform the development of new and improved artificial monolayer compounds.
- New and improved monolayer compounds being developed by the Cooperative Research Centre for Polymers group at Melbourne University.

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