A ‘Universal Design Framework’ for installation planning and operational management of evaporation-suppressing films on agricultural reservoirs

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Abstract

In Australia, the efficient use of stored agricultural water is critical as the population pressure and the variability in annual rainfall increase. One technique for reducing evaporation from larger open water reservoirs (>10ha) is the use of a monomolecular film. Highly variable performance attributed to the deleterious effects of wind and wave action discouraged adoption of the technology in the past. However, recent research has identified other contributing factors. In order to improve field performance and confidence in monolayers, a Universal Design Framework (UDF) has been developed. The UDF informs the selection of monolayer material and applicator system design for any given site; and informs and enables the automation of, day-to-day operational management. Also, the UDF can accommodate the wide range of environmental and operational factors encountered in the management of agricultural reservoirs, to calculate an optimal application system design and application strategy.

Keywords: evaporation suppression, agricultural water management, monolayer, microlayer.

1. Introduction

Certain chemicals which form a continuous monomolecular layer (‘monolayer’) on a water surface have long been known to inhibit evaporation. Much of the chemical monolayer-based evaporation mitigation research was undertaken in the 1950s, 60s and 70s centred on the use of the spreading insoluble fatty alcohols such as hexadecanol, $C_{16}H_{33}OH$ and octadecanol $C_{18}H_{37}OH$, (abbreviated to C16OH and C18OH respectively) (Barnes, 2008). Many researchers from this era reported highly variable field performance results, (anywhere from 0-43% efficiency: McJannet et al., 2008), attributing the highly variable evaporation reduction achieved to film volatilisation, drift, beaching on the lee shore and waves which break-up or submerge the film (Fitzgerald and Vines, 1963; Frenkiel, 1965; Crow, 1963; Reiser, 1969). In summary, Mansfield (1962) stated:

> “It is clear that no one method of applying/spreading (monolayer) material is suitable for all locations. Factors such as storage size and shape, wind pattern, and the costs of material and labour affect both the feasibility of each technique and the details of its use.”

Failure to address this requirement has undoubtedly contributed to the lack of commercial adoption and development in the use of monolayers, despite evidence of useful evaporation suppression performance.

Drought and near-drought conditions over much of southern Australia in the last decade has encouraged research into improving monolayer performance. The Cooperative Research Centre for Irrigation Futures (CRC-IF) and the National Centre for Engineering in Agriculture

(NCEA) are collaborating with the common aim of achieving this goal. The results of recent research at the NCEA highlight deficiencies in currently-available monolayer products, but also the potential for significant improvements in both selection of the appropriate monolayer product and in the application technology (Craig et al., 2005). New monolayer materials are being developed, which have already demonstrated superior performance over existing products in preliminary trials. Also, prototype ‘smart’ autonomous application systems have been developed to allow the adaptive and spatially dynamic application of monolayer in accordance with on-site weather conditions (Brink et al., 2009; Symes et al., 2010).

In addition, recent studies have indicated the potential for the surface film that naturally occurs on fresh water bodies (a microlayer), to interact with and adversely affect artificial monolayers (Pittaway and van den Ancker, 2010). Natural microlayers are produced by hydrophobic plant waxes, phenolic compounds and other humified material, which concentrates microbial populations capable of utilizing these materials as organic substrates. Hydrophobic fatty alcohols with carbon chain lengths of 16 are readily converted to lipid storage compounds by aquatic microbes, explaining why related compounds such as the monolayer hexadecanol (C16OH) is highly susceptible to microbial degradation. Studies also reveal that relative to northern European lakes, Australian ‘brown water’ storages have highly concentrated microlayer communities, due to the coincidence of leaf and bark fall with low rainfall (Pittaway and van den Ancker, 2010). This variation in the concentration of humified organic compounds in the storages is associated with both the volume of the storage, and the riparian vegetation within the water catchment.

To utilise hydrophobic organic compounds in the microlayer, aquatic bacteria must produce biosurfactants to attach to and to emulsify the compounds. In clean water laboratory trials, increasing the carbon chain length (from C16OH to C18OH) can improve the resilience of artificial monolayers to microbial degradation. However, even the most microbially resilient monolayer of this basic form was still found to be susceptible to disruption when placed on ‘brown water’ (from Narda Lagoon, Pittaway et al., 2009)

Despite advances in monolayer knowledge and technology, there are still some fundamental questions on the practicalities of deployment and operation that remain unanswered. These are principally:

- criteria for selecting the most appropriate monolayer material,
- the type of application system and the site-specific configuration required, and
- the amount and re-application rate of monolayer to be applied.

In order to answer these questions, a strategic approach has been devised for the use of monolayer on a reservoir for evaporation mitigation, and is set out in this paper. The approach recognises that every reservoir will have a specific set of user and environmental considerations, which leads to a unique set of operational requirements. In order to capture and utilise this information a Universal Design Framework (UDF) has been developed.

The UDF takes into account the following parameters: economics (i.e. cost of water), water storage factors, climate and weather factors, and water quality and biological characteristics. Once these parameters are specified, the UDF is used to determine:

(1) the most suitable monolayer material/s via the comparison of water quality and biological characteristics of the particular site to those of benchmark reservoirs and product performance; and

(2) the most effective application strategy and operational requirements via a surface film dispersion simulation platform which enables rapid evaluation of product spatial distribution under a range of different environmental conditions.

The results populate decision charts which then form a specification for the design and operation of a monolayer application system unique to that specific agricultural reservoir.

2. Selecting Suitable Monolayer Materials

To inform usage (1) of the UDF, three reservoirs within South East Queensland, Australia (SEQ) were benchmarked with respect to water quality and biological characteristics. Qualitative assessments were made of water source/s, water colour, turbidity, catchment vegetation type and storage size. Water chemistry was also characterised using pH, electrical conductivity (EC) dissolved oxygen, biochemical oxygen demand and ultra-violet (UV) absorbance. In addition, the performance of two different monolayer compounds was assessed in the laboratory with respect to microbial degradation, evaporative resistance and surface pressure. The microbial degradation was determined using a common freshwater bacterium with a monolayer provided as the sole organic carbon source (Figure 1). The evaporative resistance and surface pressure for both clean water (Figure 2) and brown water from Narda Lagoon (Figure 3) were determined on a Langmuir trough using standard techniques (Barnes and Gentle, 2005).

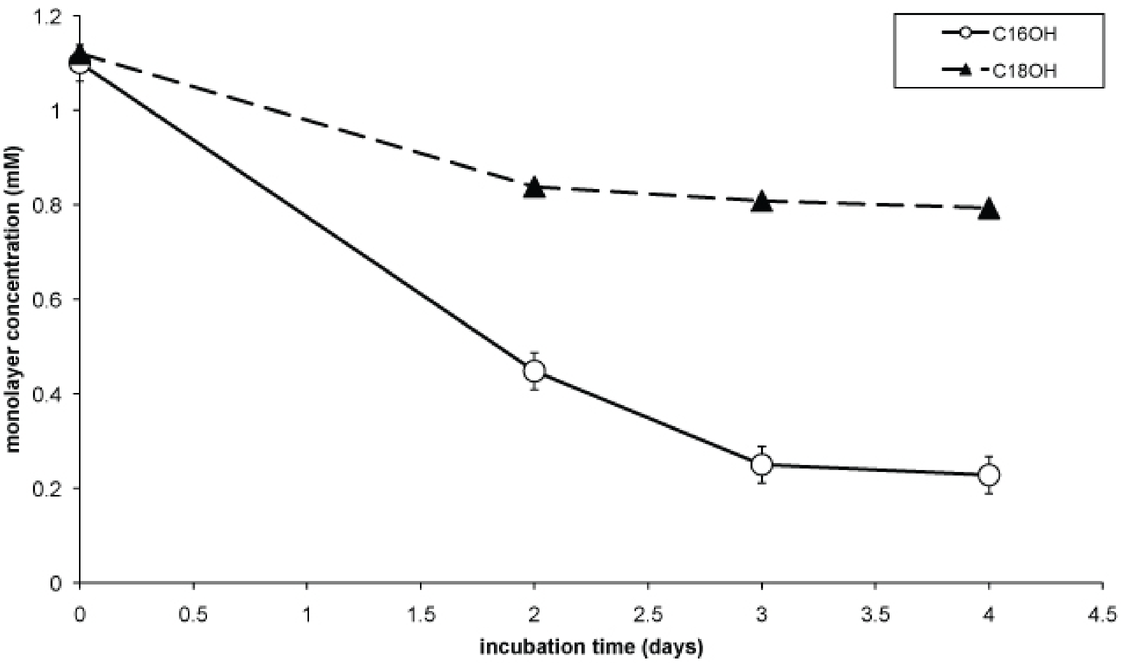


Figure 1: Degradation of two monolayer compounds supplied as the sole carbon source for the common freshwater bacterium *Acinetobacter* in a mineral salts medium. The resilience of the two fatty alcohols C16OH and C18OH were compared. Chloroform was used to extract the monolayer in the medium after two, three and four days of incubation prior to analysis using a gas chromatograph.

The laboratory performance of the two monolayer compounds was matched to the biological conditions recorded for each of the three SEQ benchmark reservoirs. Field-derived information on the potential for microlayer compounds to interfere with monolayer performance, and on the population density and activity of monolayer-degrading bacteria was used to predict the likely performance of the two monolayer compounds in reducing evaporative loss when applied to the three benchmark reservoirs. Key water quality criteria that best predicted the performance of a specific monolayer product applied to a reservoir

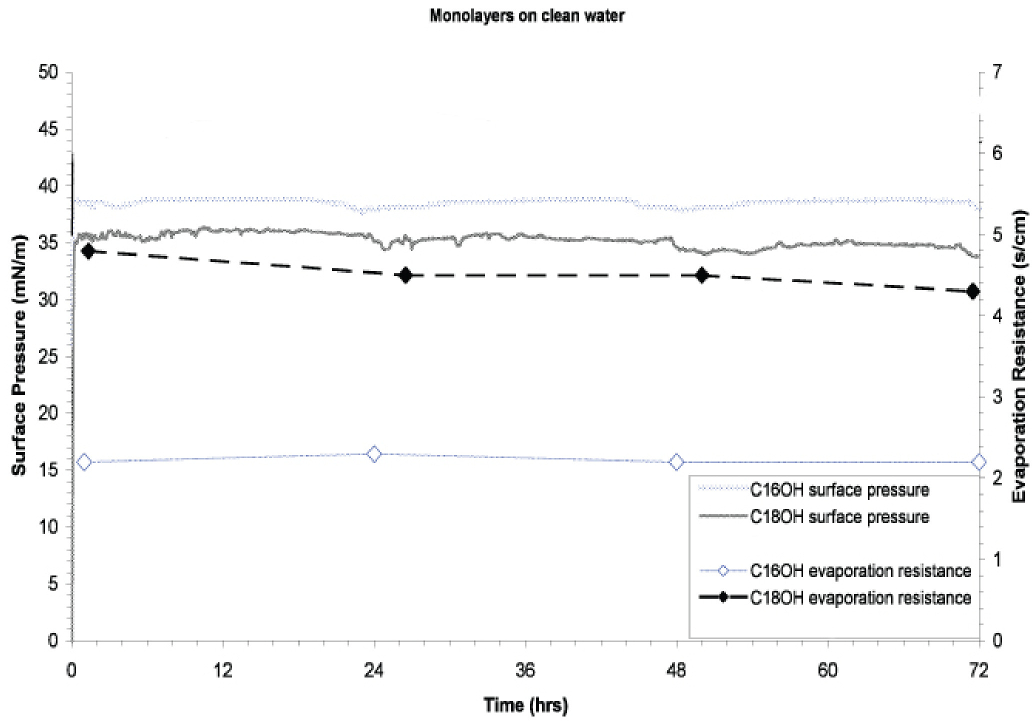


Figure 2: Laboratory (Langmuir trough) measurements of surface pressure and evaporative resistance of the same two monolayer compounds applied to clean water.

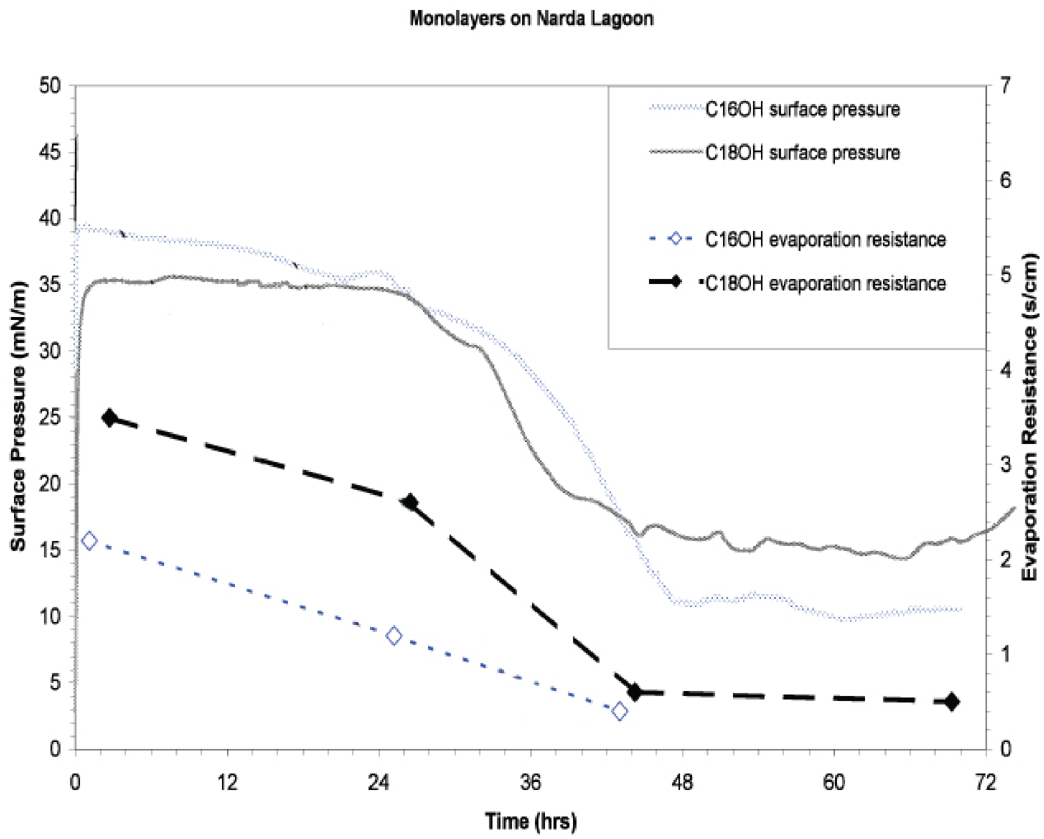


Figure 3: Laboratory (Langmuir trough) measurements of surface pressure and evaporative resistance of the same two monolayer compounds applied to brown, Narda Lagoon water.

were selected for use in a decision support system. The key indicators are history and frequency of algal blooms, measured UV absorbance of a water sample, water colour and storage size. A decisions table capturing this information was produced (Table 1) to allow numerical comparisons to be made between the SEQ benchmark reservoirs and another nominated reservoir (once characterised with respect to the key indicators) to determine a best match. The best match will then identify the most suitable monolayer compound/s for the nominated reservoir.

Table 1: Decision table capturing the water quality attributes of three water storages (Pittaway et al., 2009) were matched with the performance specifications of two monolayer compounds to predict which product will best perform on a given storage.

Water Storage:	pH:	Algal Bloom:	UV Absorbance:	Water Colour:	Storage Size:	Suitable Monolayer/s:
Cooby Dam	8.4	no	0.14	clear	306ha	C16OH or C18OH
USQ Ag. Plot	9.1	yes	0.31	pink	0.01ha	C18OH
Narda Lagoon	8.4	no	0.45	brown	2ha	C18OH

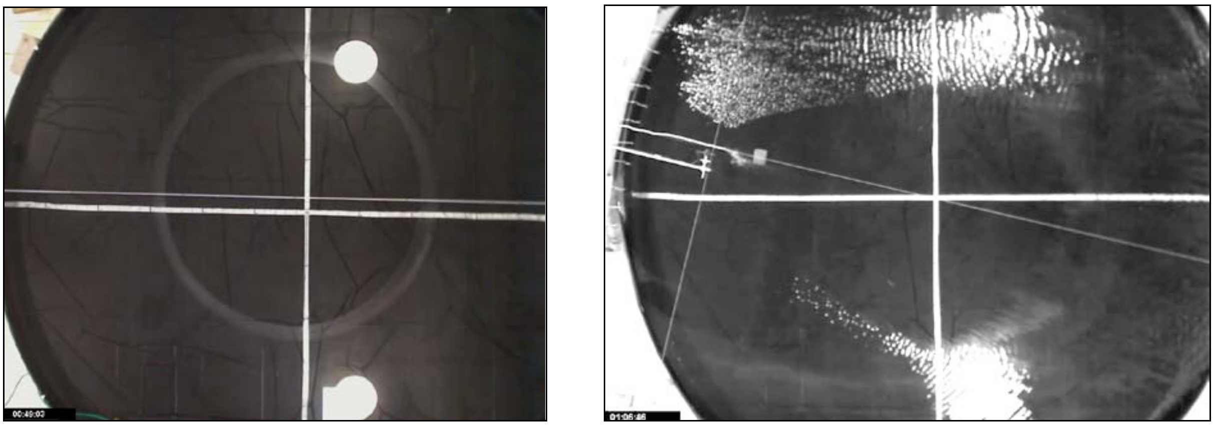
Algal blooms have the potential to disrupt artificial monolayers by increasing the population of monolayer-degrading bacteria, and by producing surface-active compounds. Of the three benchmarked reservoirs (Table 1), only the USQ Agplot was known to be affected by algal blooms. However, the Narda Lagoon reservoir had high concentrations of UV-absorbing organics in the water, which also increase the activity of monolayer-degrading bacteria and the concentration of surface-active compounds. The monolayer compound C16OH is susceptible to bacterial degradation, but less susceptible to brown water microlayer disruption (Figures 1 to 3). The C18OH monolayer is more microbially resilient, but much more susceptible to brown water microlayer disruption. The C18OH compound resists both microbial degradation and brown water disruption to a larger extent than C16OH, therefore is suitable for use on water reservoirs with a wider range of water quality attributes (Table 1). The large volume of water held in Cooby Dam, the low concentration of dissolved humified organics (low UV absorbance) and the low risk of algal bloom formation indicate that both monolayer products could be considered for use. However, for the other two reservoirs, currently only the C18OH product would be suitable for use. As new monolayer products become available, performance specifications based on microbial and microlayer tests (Figures 1 to 3) can be entered into the UDF to expand the capacity of the current decision table. Prospective users can enter the basic water quality attributes of their water storage to compute the best product match.

3. Determining Spatial Distribution of Monolayer

To inform usage (2) of the UDF a MATLAB simulation platform has been developed to allow desktop modelling of expected surface coverage under a range of geometrical and climactic characteristics for the reservoir. The model requires monolayer physical parameters and these have been determined in large-scale laboratory trials under controlled conditions for C18OH as a validation of the model. Equations were then deduced for the natural spreading ability of C18OH monolayer under zero wind conditions (and expanding circle, Figure 4a), the dispersion angle of monolayer coverage (a wedge-shape, Figure 4b) under the influence of wind, and the drift rate of monolayer, also under the influence of wind.

The natural spreading rate of monolayer was characterised under zero wind conditions because for wind speeds less than 3.6km/h, a monolayer film does not drift enough to justify continuous application (Vines, 1962; McMahon et al., 2008). Therefore, the only force driving monolayer dispersal (or surface coverage) at wind speeds less than 3.6km/h is the natural spreading ability of the monolayer. To visualise the monolayer spreading on the water surface a very thin layer of talcum powder was applied prior to the application of monolayer. Three different application rates were assessed to determine the effect on spreading rate. All experiments were digitally video recorded and analysed to produce a spreading rate equation.

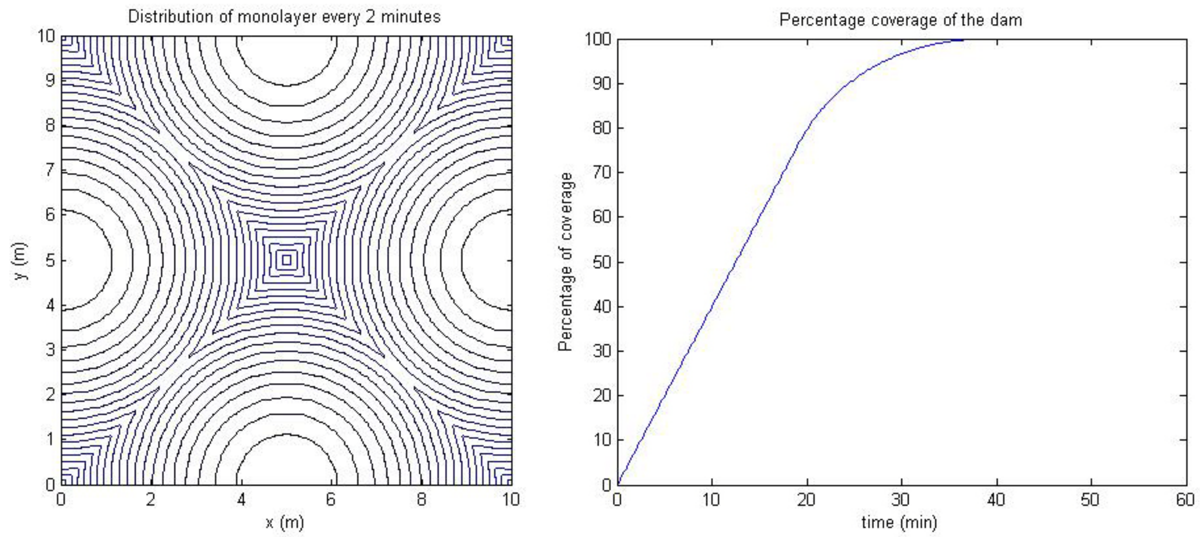
For all wind speeds greater than 3.75 km/h monolayer has been reported to spread in a wedge shape from the point of application and drift down wind at a rate of anywhere between 0.03 to 0.07 times the wind speed (McArthur, 1962; Fitzgerald, 1964). A continuous application is needed to maintain an unbroken film. Therefore, in contrast to the first spreading rate trials (Figure 4a), monolayer was applied at a continuous rate at the upwind side of the tank (Figure 4b). The monolayer dispersion angle and drift rate was determined for four different wind speeds and at three different application rates for each wind speed. Again all experiments were digitally video recorded and analysed to produce equations for change in dispersion angle and drift rate under the influence of wind.



(a) (b)

Figure 4: Images captured from video during large scale laboratory trials (performed on a 5.8m diameter test tank) to derive algorithms for monolayer spreading rate and dispersal angle: (a) Monolayer has been applied and is spreading under zero wind conditions in a linear circular shape, (b) Monolayer being applied continuously at 50 mL/min and dispersing in a wedge shape under an imposed uniform wind speed of 16.2 km/h.

Calibration of the model for desktop exploration of expected monolayer coverage is also possible for different spacing between applicators, applicator types (i.e. on-shore or floating) and placement of applicators for different reservoir sizes and shapes. The simple MATLAB simulation platform makes two assumptions, (i) that all monolayer reaching the edges of the storage is permanently lost; and (ii) that no monolayer is lost to volatilisation and/or submergence. Although both are simplifications, (i) it is likely that any monolayer not beached would most likely have little if any evaporation suppressing ability by that stage; and (ii) further experimental work is planned to quantify monolayer losses to volatilisation and/or submergence. Figure 5 shows an example of the graphical outputs from the MATLAB simulation.



(a) (b)

Figure 5: An example of the graphical outputs from the MATLAB simulation showing (a) the expected surface coverage as boundary contours at two-minute intervals, for a square reservoir 10m x 10m under a 0km/h wind speed having four on-shore applicators placed half way along each side; and (b) the percentage of surface coverage over time.

4. Application System Configuration and Operational Requirements

For large dams (>10ha) with a regular shape (i.e. square, rectangular, circular, triangular or trapezoidal), optimal surface coverage is best achieved by a number of fixed application points on-shore and also (for larger storages) within the reservoir space (i.e. floating). In order to determine the numbers of each applicator type and their arrangement on-site for a nominated reservoir, the MATLAB simulation platform is used. The inputs required to determine the above are size of the reservoir, orientation and regional historical climactic data for prevailing wind speeds and wind directions.

Many researchers have reported that the application of monolayer becomes impractical at a certain threshold wind speed, hence, monolayer application is stopped once that wind speed is reached. Researchers have report this threshold wind speed to be as low as 16km/h (Walter, 1963) and as high as 40km/h (Reiser, 1969). For initially modelling the dispersion of monolayer a maximum threshold wind speed is assigned. A number of simulation iterations are then performed for a combination of different applicator types, their respective numbers and arrangements to determine which combination will provide acceptable coverage under the nominated threshold wind speed (optimal combination). Clearly, choice of an ‘acceptable’ coverage value (percent) is an economic decision for the user: a high value implies more closely-spaced applicators.

The optimal combination is then used to quantify anticipated monolayer usage over a specified period using regional historical wind speed and wind direction data. Monolayer usage is quantified for both times of application and quantity of material applied. The specified period is basically when the application of monolayer is judged to be economically viable by the user. Then regional historical wind speed and wind direction data for this period is used within the simulation. This data is typically averaged for every hour; therefore, application strategies within the simulation are made hourly. The application rate of monolayer is equal to the predicted removal rate and is determined using the hourly averaged wind speed, which informs the drift rate (via equations from laboratory trials) and hence the removal rate. Simple decisions are also made of which applicators to apply the monolayer from according to the averaged hourly wind direction.

The amount of monolayer applied from each applicator over the specified period is then automatically quantified during the simulation. This information can then be used to determine a range of expected flow rates for each applicator. Once a flow rate range is known for each applicator, componentry such as pumps, nozzles, tubing and storage reservoirs can be sized accordingly.

5. Conclusions

The commercial adoption of monolayer technology as a water conservation strategy failed in the past due to variable field performance, and practical problems associated with dispensing the product. Recent research highlights there is no 'one-size-fits-all' monolayer product, application system arrangement or application strategy for reducing evaporative loss from reservoirs. The Universal Design Framework (UDF) approach will address these issues in three ways:

1. **Monolayer Selection:** The most appropriate monolayer product is selected according to the water quality and biological characteristics of the nominated reservoir to ensure the best potential for evaporation mitigation.
2. **System Configuration:** Desktop modelling of the expected surface coverage using the nominated reservoirs size, shape, historical wind speeds and directions to determine the number of applicators required and their arrangement on-site to ensure effective surface coverage with monolayer.
3. **System Operation:** Application strategies within the MATLAB simulation inform when to and when not to apply monolayer and from which applicators it would be best to apply monolayer from. The simulation also quantifies the amount of monolayer applied from each applicator which can are used as a design specification to size pumps, nozzles, tubing and storage reservoirs for each applicator.

The UDF will also be a useful tool for assisting dam owners in planning, designing and utilising a tailored monolayer-based application system for evaporation mitigation according to their unique economic and seasonal conditions.

Acknowledgements

This research was funded by the Cooperative Research Centre for Irrigation Futures, including the corresponding author's international travel from Australia to attend this conference. The authors would like to thank staff from the National Centre for Engineering in Agriculture for their assistance and support. The authors are also grateful to Michael Hertzig, PhD student at the University of Queensland, for the formulation and supply of the monolayer material.

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