



Australian Government
National Water Commission

New technology to reduce evaporation from large water storages

**Emma Prime, Andy Leung,
Diana Tran, David Solomon,
Greg Qiao, Ian Dagley**

Waterlines Report Series No 80, June 2012



Waterlines

A SERIES OF WORKS COMMISSIONED BY THE
NATIONAL WATER COMMISSION ON KEY WATER ISSUES

Waterlines

This paper is part of a series of works commissioned by the National Water Commission on key water issues. This work has been undertaken by the CRC for Polymers in collaboration with the National Program for Sustainable Irrigation on behalf of the National Water Commission.

© Commonwealth of Australia 2012

This work is copyright.

Apart from any use as permitted under the *Copyright Act 1968*, no part may be reproduced by any process, without prior written permission.

Requests and enquiries concerning reproduction and rights should be addressed to the Communications Director, National Water Commission, 95 Northbourne Avenue, Canberra ACT 2600 or email bookshop@nwc.gov.au.

Online/print: ISBN: 978-1-921853-93-7

New technology to reduce water evaporation from large water storages, June 2012

Authors: Emma Prime, Andy Leung, Diana Tran, David Solomon, Greg Qiao, Ian Dagley.

Published by the National Water Commission
95 Northbourne Avenue
Canberra ACT 2600
Phone: 02 6102 6000
Email: enquiries@nwc.gov.au

Date of publication: June 2012

Cover design by: Angelink
Front cover image courtesy of Geoff O'Shannassy

An appropriate citation for this report is:

Prime E, Leung A et al, 2012, *New technology to reduce water evaporation from large water storages*, Waterlines report, National Water Commission, Canberra

Disclaimer

This paper is presented by the National Water Commission for the purpose of informing discussion and does not necessarily reflect the views or opinions of the Commission.



Australian Government
National Water Commission



Contents

Executive summary	ix
1. Introduction	1
2. Literature review	2
2.1 Monolayers	2
2.2 Laboratory testing	3
2.3 Commercial products	4
2.4 Field trials	5
2.5 Environmental implications	5
3. Experimental design and data analysis	7
3.1 Design	7
3.2 Analysis	7
3.3 Reproducibility	7
4. Formulation	9
4.1 Chemical system	9
4.2 Physical formulation	9
5. Laboratory testing	10
5.1 Introduction	10
5.2 Wind resistance—small scale	10
5.3 Longevity of film	13
5.4 Spreading rate	15
5.5 Wind/wave resistance—medium scale	16
6. Field trials	20
6.1 Data analysis	21
6.2 Dookie, Victoria	23
6.3 Yanco, New South Wales	29
6.4 Logan's dam, Forest Hill, Queensland	33
6.5 St George, Queensland	37
6.6 Field trial conclusions	38
7. Product deployment	40
7.1 Solid applicator	40
7.2 Liquid applicator	40
7.3 Modelling	41
8. Environmental testing and approvals	42
8.1 Toxicity testing	42
8.2 Ready biodegradability	42
8.3 Environmental report	42
9. Economic analysis	44
9.1 Cost of saving water	44
9.2 Water market analysis	45
10. Commercialisation plan	46
11. Glossary	47
12. Bibliography	48
12.1 Further information	50

Tables

Table 1: Results from the spreading test showing the equilibrium pressure reached, time taken to reach this pressure initially and to re-equilibrate after disturbance.	16
Table 2: Details of samples tested in the wind and wave tank facility at Griffith University.	18
Table 3: Water sample analyses for water used in trough Trial 1.	25
Table 4: Trough Trial 1 set-up.	25
Table 5: Trough Trial 3 set-up.	27

Table 6: Evaporation ponds Trial 1 set-up.	29
Table 7: Evaporation ponds Trial 2 set-up.	29
Table 8: Water channel Trial 1 set-up.	31
Table 9: Water channel Trial 2 set-up.	31
Table 10: Water channel Trial 3 set-up.	32
Table 11: Water channel Trial 4 set-up.	33
Table 12: Average water allocation trading prices for the southern connected Murray– Darling Basin over recent years.	45

Figures

Figure 1: Schematic diagram of a monolayer on the water surface.	2
Figure 2: Structure of commonly used monolayer compounds: cetyl alcohol (1- hexadecanol, C16OH) and stearyl alcohol (1-octadecanol, C18OH).	3
Figure 3: Langmuir trough—apparatus commonly used for investigating monolayer properties. (Photo E Prime)	4
Figure 4: Schematic diagram of wind tunnel set-up for parallel attack.	11
Figure 5: Mass of water lost over time for EX1, EX2 and EX3 (1 mg/mL solutions) compared to a control with no monolayer, under exposure to parallel wind at 25 km/hr.	12
Figure 6: Mass of water lost over time for EX2 and EX3 solid formulations compared to a control with no monolayer, under exposure to angular wind at 25 km/hr.	13
Figure 7: Langmuir trough set-up to measure longevity of the surface film, showing top- down and side views.	14
Figure 8: The percentage of monolayer film remaining on the water surface as a function of time.	15
Figure 9: Schematic diagram of the spreading rate test.	16
Figure 10: The wind and wave tank set-up showing the external structure enclosing the tank and the blower situated above the water surface. (Photo P Schouten)	17
Figure 11: Cumulative water saving of different formulations compared to the control (no monolayer) after exposure to 24 hours of parallel wind.	18
Figure 12: Location of field trial sites and average evaporation levels across Australia.	21
Figure 13: Cumulative water loss (mm) from all channels in Trial 3 at Yanco.	22
Figure 14: Schematic showing how water savings were calculated for field trials using automatic water level sensors.	22
Figure 15: Cumulative water saving percentage of different formulations compared to the control channel for Trial 3 at Yanco.	23
Figure 16: Layout of the six troughs for the first series of small-scale field trials at Dookie. (Photo E Prime)	24
Figure 17: New layout of the six troughs for Trial 3 onwards (shown alongside the three large evaporation ponds). (Photo A Leung)	26
Figure 18: Odyssey's capacitance water level sensor probe and the PVC shroud installed in the evaporation ponds and water troughs. (Photo A Leung)	27
Figure 19: Large evaporation ponds installed at Dookie. Each pond has a surface area of 135 m ² . (Photograph: A. Leung)	28
Figure 20: Lined sections of an old irrigation channel at Yanco Agricultural Institute. (Photograph: A. Leung)	30
Figure 21: The position of nine possible addition sites at Logan's dam.	34
Figure 22: An advancing front of suppressant from the foreground towards the back of Logan's dam shown by the smooth water surface in the image. (Photograph: G. O'Shannassy)	35
Figure 23: The level of water lost to evaporation, measured by eddy covariance, on two successive days under essentially identical evaporation conditions. The dose of evaporation suppressant applied on the second day (29 March) was much larger.	36
Figure 24: An image of the dam taken during the trial on 29 March 2011. It shows a smooth surface across the dam indicating the surface of the dam is well covered with the suppressant. (Photograph: G. O'Shannassy)	36
Figure 25: Two of the three dams selected for large-scale field trials at St George, Queensland. (Photographs: A. Leung).	37

Figure 26: Solid application system identified and purchased. (Photograph: Osprey Pty Ltd).....	40
Figure 27: Plot of the cost of saving the water in \$/ML versus the millimetres of evaporation suppressed for daily addition of three different levels of monolayers.	44

Abbreviations and acronyms

C16OH	Cetyl alcohol (1-hexadecanol)
C18OH	Stearyl alcohol (1-octadecanol)
CRC	Cooperative Research Centre
CRC-IF	Cooperative Research Centre for Irrigation Futures
CRC-P	Cooperative Research Centre for Polymers
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EX1	Evaporation suppressant 1
EX2	Evaporation suppressant 2
EX3	Evaporation suppressant 3
LOEC	Lowest observed effective concentration
NSW	New South Wales
OECD	Organisation for Economic Cooperation and Development
PVC	Polyvinyl chloride
Qld	Queensland
UniMelb	The University of Melbourne
UQ	The University of Queensland
USQ	The University of Southern Queensland
YAI	Yanco Agricultural Institute

Measurements

°C	Degrees Celsius
cm	Centimetre
\$/ML	Cost (dollars) per megalitre
GL	Gigalitres
GL/year	Gigalitres per year
ha	Hectare
km	Kilometre

km/hr	Kilometres per hour
ML	Megalitre
MΩ.cm	Mega ohm-centimetre
m	Metre
m ²	Square metre
m/s	Metres per second
μL	Microlitre
mg	Milligram
mg/L	Milligram per litre
mg/mL	Milligram per millilitre
mm	Millimetre
mN/m	Milli-Newtons per metre
NTU	Nephelometric Turbidity Units
s	Second
wt%	Weight per cent

Executive summary

Evaporation from water storages is a major issue affecting agricultural regions of Australia. Annual losses potentially exceed 40 per cent of water stored. Loss of this water can lead to reduced agricultural productivity and can adversely affect the environment. Chemical ultra-thin films (monolayers) provide a method of reducing the amount of water lost, thereby increasing water security and agricultural production. Previously developed products have limitations and are not widely used. New technology recently developed in the Cooperative Research Centre for Polymers (CRC-P), however, has the potential to overcome these issues.

This report describes laboratory work carried out to evaluate and further optimise the chemical and physical formulation of the proposed new ultra-thin film product. Three chemical systems were evaluated—EX1, EX2 and EX3. These were formulated into three different physical forms; fully dissolved in organic solvent, a suspension in water, and a dry solid. The films resulting from these formulations were evaluated on their ability to control evaporation under dynamic conditions (wind), ability to maintain a surface film over time, and their spreading rate. Results from these tests demonstrated that the novel films were superior to previously researched films. Optimised products were identified to undergo field trials at various locations including Dookie (Victoria), Yanco (New South Wales) and Logan's dam (Queensland).

The summer of 2010–11 was unusually cool and wet for Australia. Rain events often interrupted field trials, making the study more challenging. Despite this, evaporation savings of 40–60 per cent were consistently observed throughout the small- and medium-scale field trials, with a saving of 38 ± 5 per cent recorded on the 16 ha Logan's dam site. The trials demonstrated that EX3 was the best performing chemical system, while the solid formulation showed the most promise. The suspension had numerous issues surrounding stability and ease of application, and the solvent system is impracticable for commercialisation due to health, safety and environmental issues. A patent application previously protected this chemical system (Solomon et al. 2010). Further work is needed to optimise the physical formulation. Production methods also need to be developed which can produce material for large-scale field trials, and potentially for eventual commercialisation.

A solid powder application system was identified and sourced for fieldwork. The best regime for applying the product was identified through a series of field trials. It required a large dose on the first day followed by smaller amounts applied daily to maintain the film's integrity and ability to suppress evaporation. The application system needs further testing using the optimised solid powder formulation.

Toxicity testing showed that the chemicals had no adverse effects on the key indicator species of daphnia, algae and rainbow fish, and ready biodegradability studies are currently underway. Toxicity consultants have compiled a draft toxicity report concluding that, based on published data and results obtained by further testing, no environmental concerns are expected for this product when used as an evaporation suppressant.

The next stage of this project is to complete further large-scale field trials during the 2011–12 summer at St George, Queensland.

1. Introduction

Annual loss of water from storages through evaporation can potentially exceed 40 per cent of water stored (Craig et al. 2007). Nationally more than 7000 GL is stored in over two million on-farm storages, with a further 80 000 GL held in registered large dams (Craig 2008). Evaporation losses from irrigation channels can also be high, with some 70 GL/year lost from channels in northern Victoria (Winter & Albrecht 2011).

The loss of water causes lost agricultural production, leading to financial stress for some farmers particularly in times of drought, experienced frequently in Australia. Low water levels also lead to water restrictions being imposed on urban regions. Reducing the amount of water lost to evaporation would improve water security for Australia and lead to increased irrigation production.

Substantial research and commercial testing on practical methods to reduce evaporation was completed recently. This indicated that current products (shadecloth, floating and modular covers) are generally prohibitively expensive (typically \$50 000 to \$100 000 per ha) for large storages (>10 ha) and irrigation channels (Craig et al. 2005, Yao et al. 2009). This is a particular issue in Queensland for example, as around 80 per cent of water is held in large storages (Craig 2005). For such large storages and irrigation channels the only potentially cost-effective evaporation control option is to use chemical ultra-thin films (~2 millionths of a millimetre thick).

Previous materials have been investigated in field trials (McJannet et al. 2008). However, the performance of these chemical ultra-thin film products was compromised by wind, water quality and volatilisation of the monolayer, so water savings were low.

Research by the CRC-P has developed a novel ultra-thin film technology capable of increasing the viability of monolayers by overcoming the recognised limitations (Solomon et al. 2010, Prime et al. 2012). To be deployed, these chemicals need to be formed into a physical product, and to undergo extensive performance testing in the laboratory, and in small- and large-scale field trials.

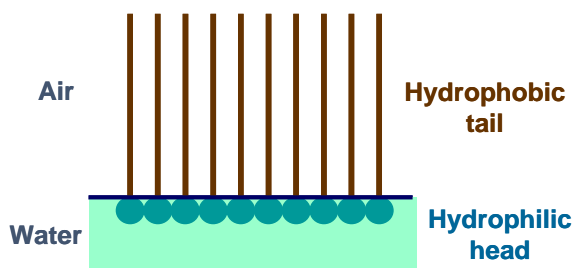
The aim of this project was to run a range of field trials to assess the effectiveness of this novel technology and to determine whether it is an improvement over previous technologies. If the technology is successful, the water savings from large on-farm storages alone could be more than 300 GL/year, with further savings expected from irrigation channels and other water storages.

2. Literature review

2.1 Monolayers

Ultra-thin surface films (often called monolayers) are typically one molecule thick and sit at the water surface as shown in Figure 1.

Figure 1: Schematic diagram of a monolayer on the water surface.



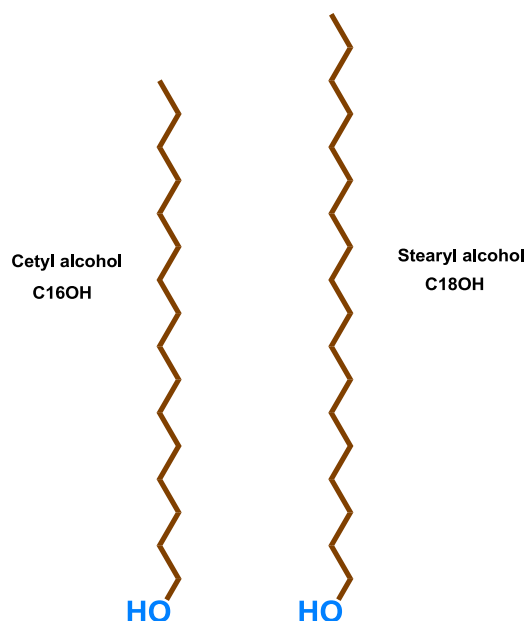
Compounds used as monolayers generally contain a hydrophilic (water-loving) head anchor into the water and a hydrophobic (water-hating) tail that packs tightly at the air/water interface. Monolayers have been used in many fields including membranes for molecular separations (Hendel et al. 1997), biomedical systems for tissue engineering and drug delivery (Vendra et al. 2007), packaging and coating materials (Lonescu et al. 2009) and water evaporation mitigation (Barnes 2008).

2.1.1 Water evaporation mitigation

Rideal first discovered that monolayers could be used to reduce water evaporation (Rideal 1925). Subsequently, Langmuir and Schaefer made the first quantitative measurements of the evaporation resistance of monolayers and demonstrated an Arrhenius-type temperature dependence of the evaporation resistance to permeation by evaporating water molecules (Langmuir & Schaefer 1943). Since these discoveries, considerable attention has been directed towards effectively suppressing water evaporation, especially from large, open water bodies (Barnes 1993, Machida et al. 2003, Gugliotti et al. 2005).

Naturally occurring fatty alcohols, cetyl alcohol (1-hexadecanol) and stearyl alcohol (1-octadecanol), have been the most commonly investigated compounds for use as evaporation suppressants (Barnes 2008, Dressler 1973, Reiser 1969). The structure of these molecules is shown in Figure 2.

Figure 2: Structure of commonly used monolayer compounds: cetyl alcohol (1-hexadecanol, C16OH) and stearyl alcohol (1-octadecanol, C18OH).



The hydroxyl group (blue in Figure 2) is the water-loving head group that sits in the water, while the hydrocarbon chain (brown in Figure 2) is the water-hating tail that packs tightly in the air, restricting the transfer of water.

To be useful evaporation suppressants, surface films need to have a high equilibrium surface pressure (an indication of how tightly packed the molecules can be without an external force), as well as the ability to reduce evaporation at this pressure (Barnes 2008). Both 1-Hexadecanol and 1-octadecanol have been shown to have these properties, saving up to 50 per cent of water lost under suitable conditions in the laboratory (La Mer & Healy 1965). Despite meeting these requirements, these molecules have generally not been considered to be sufficiently effective as water evaporation suppressants in practical situations, and have not been widely adopted. This is thought to be due to their rapid loss from the water surface, and lack of stability to wind and wave action. It is also due to the difficulty in reliably obtaining in the field the suppression performance observed under laboratory conditions—described further in Section 2.4 (Barnes 2008).

In his review of the current state of the technology, Barnes concluded that for monolayers to become viable, superior monolayer-forming materials would be needed. It would also be helpful to have better methods of deployment (2008).

2.2 Laboratory testing

For many years, important studies have been carried out in the laboratory to identify and quantify the desired chemical properties and to understand the mechanism by which monolayers reduce water evaporation (Deo et al. 1964, Barnes & La Mer 1962, Barnes 1997, Kaganer et al. 1999, Kulkarni & Katti 1982, Miller & Bavly-Luz 1962). Laboratory studies also help in selecting and developing new materials capable of reducing evaporation by providing an initial test of their effectiveness. The most commonly used apparatus for obtaining information about the properties of monolayers is the Langmuir trough, shown in Figure 3.

Figure 3: Langmuir trough—apparatus commonly used for investigating monolayer properties. (Photograph: E. Prime)



The trough is equipped with a moveable barrier, which can be used to compress and relax the surface film. A surface pressure sensor (Wilhelmy plate) at one end is used to measure the surface pressure of the water and therefore the presence and compaction of the monolayer. Information obtained from a Langmuir trough includes:

- isotherms of the surface pressure as a function of area per molecule. These provide information on the packing characteristics of the molecular film
- equilibrium surface pressure—the surface pressure at which the molecules are in equilibrium and are usually packed closely together. This is the maximum surface pressure a monolayer will achieve when used on a water body
- static evaporation suppression data (i.e. without wind effects) using the Langmuir-Schaefer method (1943)
- spreading rate on a small scale (Herzig et al. 2011).

For most experiments using the Langmuir trough, a monolayer is typically examined as a single, ideal layer. In other words, the material applied is less than is needed to completely cover the surface. The barrier is then used to compress the film to the desired surface pressure for the experiment. However, when monolayer products are used in the field, more needs to be applied to cover the surface with one ideal monolayer. This enables the film to replenish and repair if it is disrupted by wind, waves or other action, or material is lost into the atmosphere or subphase. In this report the amount of the evaporation suppressant applied to the water surface is referred to as 18x, 6x etc. This means that the amount applied is what is needed to cover the water surface with 18 (or 6) 'ideal' single monolayers. This information can be obtained from running isotherms on the Langmuir trough.

2.3 Commercial products

Two commercial products describing themselves as monolayers, or ultra-thin films to reduce water evaporation, have been released on the Australian market in recent years.

2.3.1 WaterSavr®

WaterSavr® is a solid powder, based on cetyl and stearyl alcohol mixed with a hydrated lime dispersant. Flexible Solutions International Inc market the monolayer product. Several trials have been carried out on WaterSavr®, with variable results (Morrison et al. 2008, Flexible Solutions 2006).

2.3.2 Aquatain®

Aquatain® is a silicone-based liquid which forms a film on the water surface. The film formed is not a monolayer—at 200 nm it is about 100 times thicker, based on the recommended application rates. Aquatain® is marketed by Aquatain Products Pty Ltd. Variable results have also been obtained in trials on Aquatain® (Morrison et al. 2008).

2.4 Field trials

Numerous field trials on monolayers to reduce water evaporation have been carried out over the past 60 years, good summaries of which can be found in McJannet et al. (2008) and Barnes (2008). Trials have used water bodies ranging in size from small ponds (78 m², Craig et al. 2005) up to large storages (970 ha, Bureau of Reclamation 1962). Most trials have used either cetyl or stearyl alcohol, predominately as a solid, and have found water savings ranging from 8 per cent up to 43 per cent.

A film that is considered stable on the Langmuir trough in the laboratory may not be stable on the surface of a water reservoir. A common problem in the field is the lack of film stability against wind and wave action. This can profoundly accelerate the loss of monolayer material as well as disrupt surface coverage (Barnes 2008). Previous research has stated that exposure to wind of a velocity greater than 10 km/hr (2.7 m/s) destroys the monolayer structure of cetyl and stearyl alcohol, thereby markedly reducing its ability to control water evaporation (Drummond et al. 1992, Grundy 1962). Wave action has also been found to influence the performance of monolayer films (Healy & La Mer 1964).

The development of new products with increased resistance to wind stress is critical if monolayers are to become viable.

2.5 Environmental implications

Before this technology is introduced widely, the environmental implication of using monolayers needs to be considered and addressed. Factors include impact on humans and animals (including aquatic, land and birds), the biodegradability of the material including toxicity of any degradation products, and any other effects on the aquatic environment. Fisk et al. provide a good summary of the physicochemical, biodegradation and acute aquatic ecotoxicity properties of long chain fatty alcohols including cetyl and stearyl alcohol (2009).

Cetyl and stearyl alcohol and their fatty alcohol ethoxylate derivatives, are extensively used as emollients, thickeners or stabilisers in the cosmetic industry. They are also used as lubricants and resins and therefore have United States Food and Drug Administration approval for use in the food, medicinal and cosmetic industries, indicating none to low toxicity to humans.

Less study has been done on the aquatic toxicity of these compounds, with the lack of water solubility cited as a difficulty encountered during this testing (Fisk et al. 2009). Nonetheless, the available data indicates low toxicity is expected (Fisk et al. 2009), although further testing should be carried out on the exact materials to be used as monolayer products.

Fatty alcohols and their derivatives such as fatty alcohol ethoxylates, biodegrade rapidly via both aerobic and anaerobic processes. Steber and Wierich (1985) proposed biodegradation pathways for these compounds in the effluent of a sewage treatment plant. Other research has found their biodegradation half-life in activated sludge to be less than one minute (Federle & Itrich 2006), while in natural river water, half-lives of 1.3–1.5 days were observed

(Larson & Games 1981) demonstrating the susceptibility of these compounds to biodegradation. It is expected, therefore, that monolayer materials will biodegrade rapidly in the aquatic environment.

Monolayers have been found to have only a small effect on the temperature of the water body on which it has formed (Saylor et al. 2000, Jarvis 1962). Previous testing at the University of Melbourne has found that monolayers have a negligible effect on the transfer of oxygen into the water body (data not published).

3. Experimental design and data analysis

3.1 Design

Designing an experiment carefully is critical to obtaining appropriate and useful data. Generally an experiment will be structured to answer a specific question, for example—how long does the film last on the water surface, how quickly does it spread, what effect does the reapplication rate and/or frequency have on performance? Ideally one variable should be investigated, while all others are held constant. In the laboratory this is relatively straightforward as a constant experimental environment is easy to maintain. For example, ultra-purified water can be used to reduce the number of variables in any given experiment. In the field, however, many uncontrolled variables are introduced, such as temperature, humidity, wind, rain, and water quality. This makes it difficult to compare results from different trials. In the field a single trial will ideally contain all the samples needed to draw conclusions, without having to rely on data from other trials (i.e. every trial will contain a control, with no surface film).

Three areas of research ran simultaneously throughout this project: development and optimisation of the chemical system and physical formulation, laboratory testing, and field trials. It was not easy to define an overall detailed experimental plan at the start. Rather it was developed as the project progressed using results and information obtained from completed experiments to determine the best path to follow for subsequent work. For example, the general aims for the field trials were defined at the beginning (as outlined in Section 6), however, for each specific trial the latest information from formulation development, laboratory and any previous field trials, was analysed with conclusions then used in detailed planning of the next trial.

3.2 Analysis

The person undertaking the trial carefully analysed data from all experiments. In most cases other members of the project team also analysed results and discussed them in project meetings. More detailed examples of data analysis, particularly for the field trials, are discussed in the relevant sections.

3.3 Reproducibility

To be confident of results it is best to replicate experiments. This provides information on experimental uncertainty and reproducibility. In the laboratory it is straightforward to replicate experiments with accurately controlled variables (e.g. temperature, humidity, water quality). In all the laboratory experiments described in Section 5 each test was run at least twice, preferably three times. The results in Section 5 show that good reproducibility was generally achievable in the laboratory.

It is more difficult to obtain high levels of reproducibility in field trials. It is not possible to run strict replicate field trials when conditions such as temperature and wind inevitably vary between trials run at different times. Consequently reliability of the results was ensured by carefully analysing the data, estimating the likely contribution of experimental uncertainty, comparing general trends across multiple trials, (particularly those performed in the same

location), and often, comparing the same chemical system with a different physical formulation run in the same trial. Data analysis for the field trials is discussed in detail in Section 6.1, where it is explained that water saving percentages obtained from the field trials generally have an error of ± 5 percentage points.

Experimental reproducibility is discussed further throughout the report.

4. Formulation

4.1 Chemical system

The CRC for Polymers has developed a superior surface film system, which is the subject of a patent application (Solomon et al. 2010). This project examines three experimental novel evaporation suppressant systems based on this technology: EX1, EX2 and EX3.

4.2 Physical formulation

The chemical system needs to be processed into a physical form that can be applied to the water surface in a controlled, reproducible and commercially viable manner. Developing these physical formulations was an ongoing, iterative process that continued throughout the entire project, in parallel with laboratory and field trials. Results were analysed and findings continually fed back into the physical formulation development program.

The requirements for a developed physical formulation were:

- to allow the chemical system to maintain good evaporation control
- ease of applying it to the water surface, both by hand and by future automatic dispensing units
- the ability to disperse and spread across the water surface promptly
- the ability to meet any likely environmental, health and safety requirements for future end-users
- the potential to scale up and eventually commercialise a suitable product.

Three different classes of physical formulation were identified and a range of formulations developed in each class, namely:

- **Solvent**—when testing in the laboratory the preferred solvent system is one in which both components are fully dissolved. This allows the amount of material applied to the water surface to be precisely measured, especially for the smaller laboratory-scale experiments (where 1–2 mg of material is required, making it difficult to weigh the precise amount of a solid product). These solutions can contain between 0.1–10 wt% active components. However, using solvent for a commercial product is impracticable, given the potential health, safety and environmental issues.
- **Suspension**—suspensions were prepared using a high speed mixer to suspend the active components in water at a solids loading of 10 wt%. Various mixing speeds, time, and additives were investigated.
- **Solid powder**—the product has also been made into a fine solid powder by grinding. The solid may require additives to obtain a final product with the desired physical properties, therefore the products contained between 50–100 wt% of the active components.

5. Laboratory testing

5.1 Introduction

Most of the formulation work was conducted at the University of Melbourne—as was the first stage of testing for any new chemical or physical formulation. The most important test was for wind resistance. This measured the ability of the surface film to control evaporation when exposed to wind, a critical parameter if these films are to be commercially viable. Other tests to further evaluate the formulations could also be carried out in the laboratory to assess spreading rate, longevity of the film on the water surface (under controlled conditions) and static evaporation control.

Following evaluation in the university's laboratories, the most promising formulations were then tested at larger scales including field trials (as described in Section 6) or testing in the specially-developed wind and wave tank at Griffith University (Gold Coast) as described in Section 5.5.

5.2 Wind resistance—small scale

A significant failing of previous monolayers was lack of resistance to wind stress (Barnes 2008). A major focus of this research has been to improve this shortcoming. A novel laboratory test needed to be developed to measure the ability of a film to control evaporation when exposed to wind stress. This test became the cornerstone of the laboratory testing procedure, as it was used to screen a wide range of chemical systems while searching for the optimal one. It also proved invaluable in screening various physical formulations of the potential commercial product.

5.2.1 Method

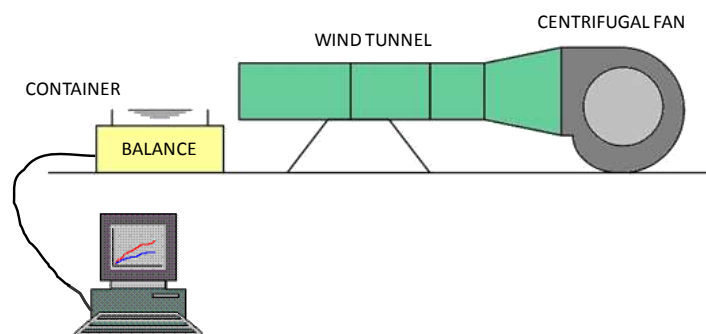
A gravimetric method was used to measure evaporation reduction under exposure to wind by monitoring the change in weight of the water over time. The wind was generated by a centrifugal fan connected to a custom-made wind tunnel (60 cm long, 21 cm wide and 9 cm high at the mouth) as shown in Figure 4. The wind tunnel directed the wind over the surface of the water, with a wind speed of 25 km/hr (7.0 m/s, as measured by a hot wire anemometer placed at the mouth of the wind tunnel). The mouth of the tunnel was positioned at the end of a digital weighing balance. Two wind attack angles were investigated to determine if the direction of wind affected the performance of the surface film:

- parallel attack—where the wind is directed horizontally across the water surface.
- angular attack—where the wind hits the water surface at an angle of 25°.

A plastic rectangular container filled with ultra pure water (distilled, UV-treated and filtered water from a Milli-Q system; resistivity of 18.2 MΩ/cm) was placed on top of the balance. The digital balance was connected to a computer, which was set to log the mass of the container and water every minute. Three times the amount of material required to completely cover the water surface with a monolayer was applied and left for 30 minutes to allow for solvent to evaporate and the film to equilibrate before turning on the fan. The solvent formulation was applied with a microsyringe to gently distribute droplets of material at multiple locations across the water surface, while the fine powder solid was gently placed on the water surface in the centre of the container. The change in weight of the containers was then monitored over 12 hours. If the experiment was continued after this time the level of water in the containers

dropped low enough to affect the results. A container of water with no monolayer was used as the control. All experiments were repeated three times. The entire experimental system was located in a controlled room set with ambient temperature 25°C and relative humidity 45–50 per cent.

Figure 4: Schematic diagram of wind tunnel set-up for parallel attack.



5.2.2 Results

The parallel wind test was the first test carried out on all new chemical and physical formulations during extensive, iterative and ongoing product development. Information from these tests fed back into the product design loop to enable further improvement and optimisation of the chemical and physical formulation.

While the results obtained from the parallel wind test are too numerous to display, Figure 5 shows a typical result for the different chemical systems (EX1, EX2 and EX3) in solvent (1 mg/mL), along with the accompanying control (no monolayer), for a container initially holding 800 mL of water.

Figure 5: Mass of water lost over time for EX1, EX2 and EX3 (1 mg/mL solutions) compared to a control with no monolayer, under exposure to parallel wind at 25 km/hr.

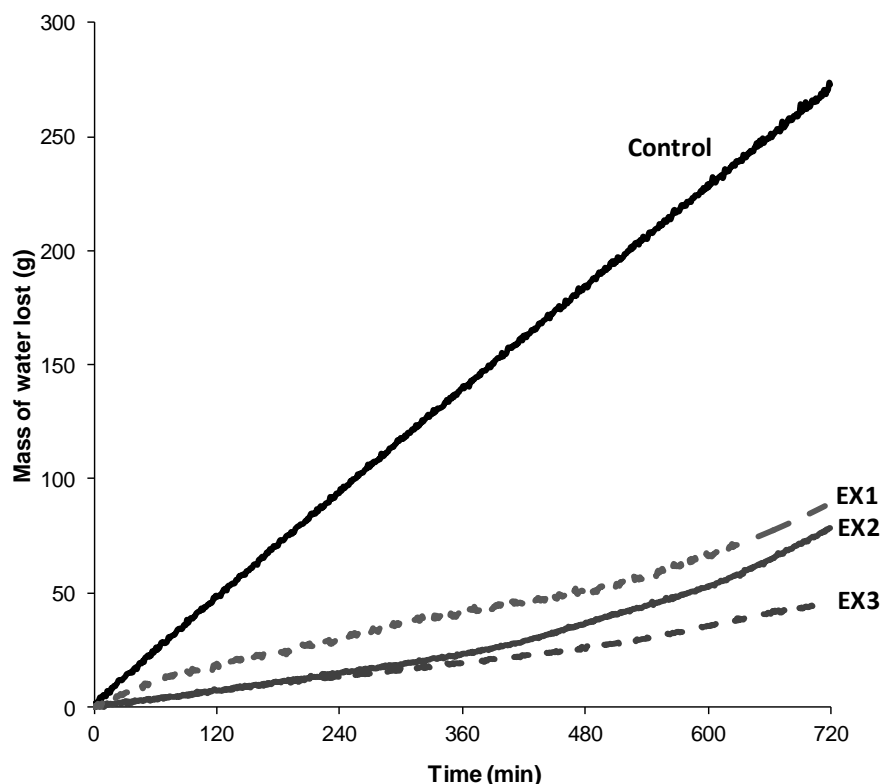
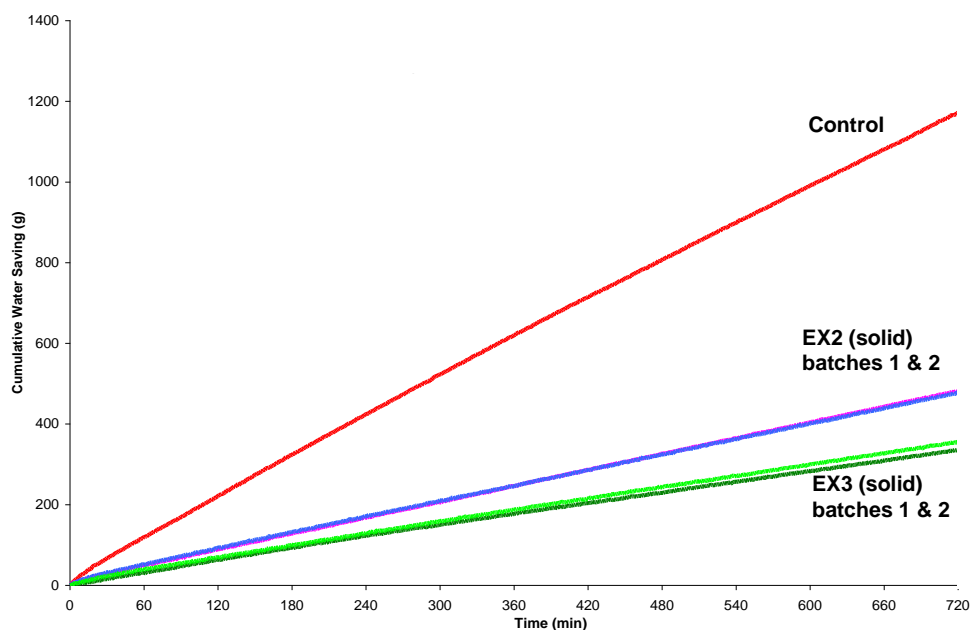


Figure 5 shows that all chemical systems suppress evaporation to some extent, as the mass of water lost is less than the control. The EX3 suppressant shows a greater ability to control evaporation under wind stress than EX1 or EX2 with 84 per cent of water saved (compared with 67% for EX1 and 72% for EX2). Repeated experiments produce very similar results with an error of ± 2 per cent.

In the open world environment the product will experience a limitless array of wind conditions so the angular wind test was introduced to provide information on the effect of the wind's angle of attack on performance. This test was also used as the main tool to assess initially the evaporation-suppressing performance of various physical formulations. Again, extensive testing was carried out in the angular wind system. Figure 6 shows a typical result for the solid formulations EX2 and EX3 for a container holding 2.6 L of water (EX1 was not tested in this experiment). In this case two batches of each formulation had been included to demonstrate repeatability of results for both the wind test experimental technique and the formulation method used to make these materials.

Figure 6: Mass of water lost over time for EX2 and EX3 solid formulations compared to a control with no monolayer, under exposure to angular wind at 25 km/hr.



The two different batches of EX2 performed equally well, demonstrating the reproducibility of both the wind testing and production methods for this solid formulation. Similarly the two batches of EX3 had reproducible results.

The angular wind test results showed the same trends as the parallel wind test, with EX3 performing better than EX2. In the two examples presented here, however, the actual savings were slightly lower in the angular wind test: 64 per cent for EX2 compared with 72 per cent, and 72 per cent for EX3 compared with 84 per cent. This is due partially to the difference in performance for the solvent and solid formulations. Typically solvent demonstrates the best performance, however, it is not a commercially viable formulation option due largely to environmental implications. A major aim of the formulation development work therefore, has been to improve the suspension and solid formulations so they perform at high levels, compared with the solvent system. It was also found that the evaporation suppressant systems showed greater savings in the parallel wind test than the angular system. This is believed to be due to the larger angle of wind attack in the angular system increasing the turbulence of the water and providing greater disturbance to the surface film, thus decreasing performance.

The wind test developed at the University of Melbourne to investigate the evaporation control performance of surface films when exposed to wind at either a parallel or angular attack angle has proved valuable as a first screen of new formulations. A formulation must have shown savings of at least 50 per cent in these tests to proceed to the next stage of testing: field trials, and/or the larger-scale wind and wave tank at Griffith University.

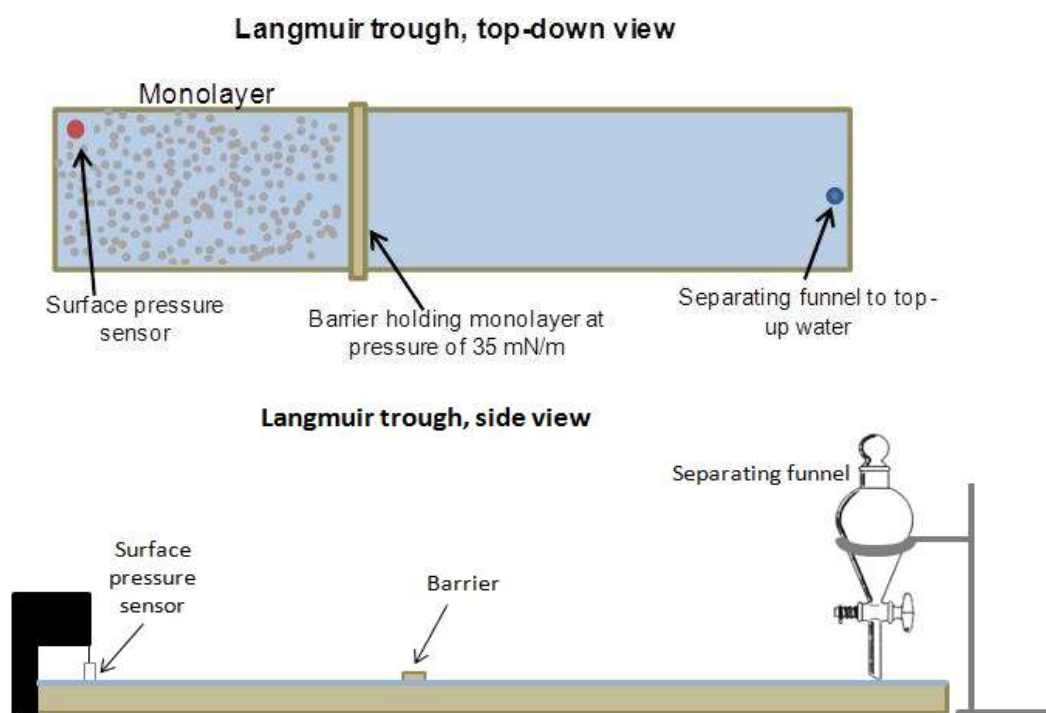
5.3 Longevity of film

If a film is to be commercially viable it needs to be able to remain on the water surface for an acceptably long time. An initial screening test can be carried out in the laboratory to determine the stability of a surface film under controlled, ideal conditions. If a film is not stable under these conditions it is not investigated further.

5.3.1 Method

A Teflon[®] Langmuir trough (76 cm x 10 cm) with a single barrier measured the longevity of the film on the water surface. The trough was filled with ultra pure Milli-Q water and allowed to equilibrate with the air at a temperature of $25 \pm 1^\circ\text{C}$. A quantity of 50 μL of the monolayer forming material in solvent was applied to the water surface and left for 30 minutes to allow the solvent to evaporate. The barrier was then used to compress the monolayer to a surface pressure of 35 mN/m, after which the barrier was instructed to hold the monolayer constant at that pressure. As the monolayer material was lost from the water surface either by volatilisation into the atmosphere or dissolution into the water subphase, the barrier was forced to compress the monolayer to maintain this surface pressure. The change in surface area over time was recorded continuously for 24 hours. This was subsequently correlated to the rate of loss of monolayer material, and the results were presented as the percentage of monolayer material remaining on the water surface as a function of time. The water level in the trough was maintained by placing the tip of a separating funnel (held by a retort stand) filled with Milli-Q water, on the side of the barrier without monolayer. The change in height allowed water in the separating funnel to flow, thus maintaining the water level within ± 2 mm. A schematic of the test set-up is shown in Figure 7.

Figure 7: Langmuir trough set-up to measure longevity of the surface film, showing top-down and side views.



5.3.2 Results

The stability of the novel film technology was compared to the compounds most commonly investigated in previous studies 1-hexadecanol (cetyl alcohol, C16OH) and 1-octadecanol (stearyl alcohol, C18OH). All samples were in solvent at a concentration of 1 mg/mL. The results are shown in Figure 8.

Figure 8: The percentage of monolayer film remaining on the water surface as a function of time.

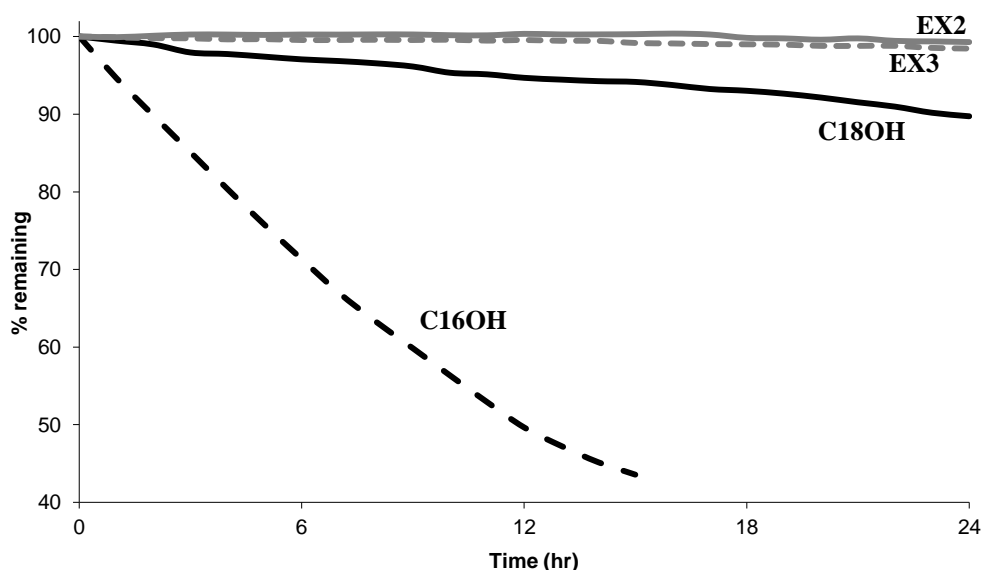


Figure 8 shows that EX2 and EX3 both have significantly improved longevity on the water surface when compared to cetyl alcohol (C16OH) and stearyl alcohol (C18OH). It is believed that if a film does not demonstrate sufficient stability under the controlled conditions used here (air and water temperature $25 \pm 1^\circ\text{C}$, ultra pure water and no wind), then it has little chance of surviving for long in the field where conditions vary widely and are more extreme.

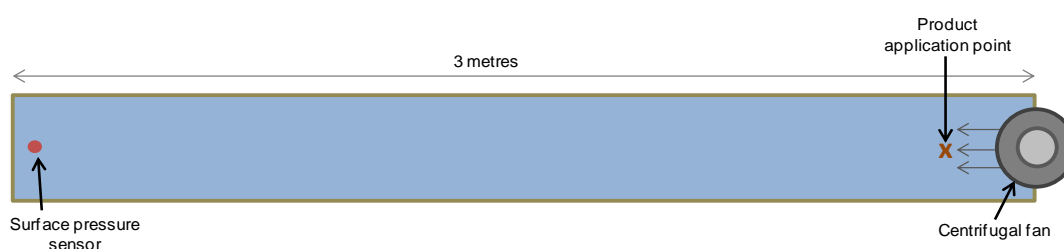
5.4 Spreading rate

For this technology to be successful it is crucial that the surface film formulation is able to spread across the water surface and self-assemble into an equilibrium close-packed film that is capable of controlling water evaporation. Ideally a product will reach this closely-packed equilibrium pressure quickly, both initially and also after disturbance by wind, birds, boats and other factors. Therefore a custom-designed system has been developed to test the spreading rate of various formulations as well as the ability to re-spread following disturbance.

5.4.1 Method

A 3 m length of PVC (polyvinyl chloride) tubing (30 cm diameter) was cut open and sealed at both ends. A surface pressure sensor (Wilhelmy plate) was installed at one end and a centrifugal fan was installed at the other. The tube was in a room where the temperature was controlled at $25 \pm 1^\circ\text{C}$, and was filled with tap water. The surface film formulation was applied at the end of the tube closest to the fan and the surface pressure at the opposite end was recorded over time. Also recorded was the time taken for the film to reach equilibrium. Once the surface pressure had reached equilibrium the centrifugal fan was turned on for 30 minutes. The ability of the surface film to re-equilibrate was monitored. The fan was cycled on and off every 30 minutes for 24 hours. Each sample was repeated three times. A schematic of this set-up is shown in Figure 9.

Figure 9: Schematic diagram of the spreading rate test.



5.4.2 Results

The spreading rate of the various experimental formulations has been tested. Initially the formulations were applied as solid powders to measure the spreading rate of the actual material, without influence from solvent or other potential additives. The next stage will involve testing the developed physical formulations to ensure the formulation method and any additives do not compromise the spreading rate. The initial time taken for the surface film to equilibrate was recorded, before the film was disturbed and then re-equilibration time recorded. Replicated results obtained for two solid formulations of EX2 and EX3 are shown in Table 1.

Table 1: Results from the spreading test showing the equilibrium pressure reached, time taken to reach this pressure initially and to re-equilibrate after disturbance.

<i>Product</i>	<i>Equilibrium pressure (mN/m)</i>	<i>Time to initially reach equilibrium pressure (s)</i>	<i>Time to re-equilibrate after fan switched off (s)</i>
EX2 (solid) run 1	25	500	500
EX2 (solid) run 2	28	600	500
EX3 (solid) run 1	35	100	200
EX3 (solid) run 2	37	120	200

The solid formulations spread to reach their equilibrium pressure with EX3 demonstrating a superior spreading rate. It was also found that following disturbance from the fan, all experimental formulations were able to reform a film reaching equilibrium. This indicates they should be capable of self-repair following wind, boat, or animal disruption. The replicated samples had good reproducibility in the spreading test.

5.5 Wind/wave resistance—medium scale

As well as the laboratory tests conducted under controlled conditions at the University of Melbourne, field trials are also needed in outdoor environments to evaluate formulations under more realistic open conditions. It is a large step from the laboratory to field trials with many variables being introduced at once, including size of experiments, fluctuating ambient temperature, varied wind speed and direction, and impure water. Using a unique wind and wave tank facility (water surface ~6.9 m²) housed in an atmospherically-controlled environment within the School of Engineering at Griffith University's Gold Coast Campus, different formulations were evaluated to increase the size of the experiments without also introducing a wide range of uncontrolled variables. This work was done alongside developing formulations, laboratory testing and outdoor field trials so the experimental design was finalised for each trial immediately prior to testing.

5.5.1 Aims

The samples tested in the Griffith University wind and wave tank facility had two aims:

- quantify the performance of the three novel evaporation suppressants—EX1, EX2 and EX3, in reducing evaporation
- compare the evaporation suppressing capabilities of different formulation methods—solvent, suspension and solid.

5.5.2 Method

The team in the School of Engineering at Griffith University had previously designed and constructed the wind and wave tank facility for other projects. A temperature-controlled enclosure (set to a constant temperature of 23°C) was built around a rigid wave basin (dimensions: 15 m x 0.46 m x 0.85 m) to maintain consistent temperatures and a stabilised humidity range throughout each experiment. Figure 10 shows the custom built set-up, which had been designed to test the effect of wind and wave action on the water surface.

Figure 10: The wind and wave tank set-up showing the external structure enclosing the tank and the blower situated above the water surface. (Photograph: P. Schouten).



Wind was delivered inside the tank via a blower and was straightened by a cylindrical honeycomb unit before coming into contact with the water surface. After applying the product, evaporation was measured over the experimental time interval by recording the change in water level using a pulse altimeter. Atmospheric parameters such as relative humidity, air temperature and water temperature were also monitored for each trial.

The tank was filled with potable tap water and all trials were carried out for 24 hours. These trials deduced the influence of wind upon the monolayers up to approximately 3 m/s (equivalent to 11 km/hr) incident at 0° to the horizontal water surface plane (parallel). The waves had amplitudes ranging from 0.2 to 0.5 cm and frequencies of up to 0.1 s.

The amount of material applied for all samples was enough to cover the entire water surface with 18 monolayers (designated 18x monolayers). The products were applied by hand at four evenly-spaced locations along the length of the water tank. The tank was emptied between each trial and rinsed to ensure any remnants were removed. It was then refilled with fresh water. Each sample was repeated twice.

5.5.3 Results

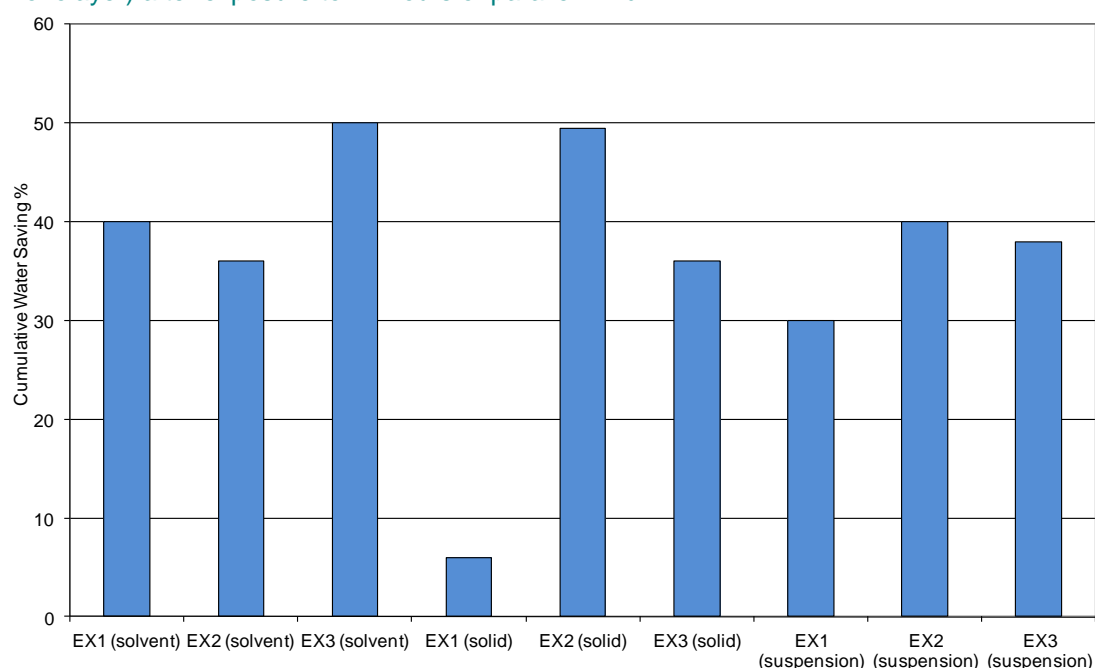
A wide range of samples was tested throughout the project. Table 2 presents a selection of results showing the performance of all combinations of chemical system and physical formulation.

Table 2: Details of samples tested in the wind and wave tank facility at Griffith University.

<i>Experiment</i>	<i>System</i>
1	Control
2	EX1 (solvent)
3	EX2 (solvent)
4	EX3 (solvent)
5	EX1 (solid)
6	EX2 (solid)
7	EX3 (solid)
8	EX1 (suspension)
9	EX2 (suspension)
10	EX3 (suspension)

The cumulative savings of different formulations compared to the control run (no monolayer) after 24 hours testing with parallel wind are shown in Figure 11.

Figure 11: Cumulative water saving of different formulations compared to the control (no monolayer) after exposure to 24 hours of parallel wind.



In general, the wind testing results demonstrate that the films save 30 to 50 per cent of water compared with the control run.

In most cases EX2 performed the same or better than EX1 across these tests. When considering the wind testing results for the solvent system, EX3 outperformed EX2. This agrees with laboratory results obtained at the University of Melbourne (Section 4.2.2). A comparison should not be made with the solid and suspension formulations, as the

formulations used in this trial were in an early stage of development. Information gained from the performance of samples in this trial was fed into the design loop to improve subsequent solid and suspension formulations.

The solvent system gave the most consistent results throughout this trial. The solid and suspension samples performed inconsistently as already explained because these samples were at an early stage of development and were not yet fully optimised.

Overall, the wind and wave tank was able to show that the chemical system and physical formulation reduces evaporation on a larger scale than had been demonstrated in previous laboratory work (6.9 m^2 compared to 0.017 m^2). These results also show that scaling up the wind testing, under controlled conditions, provides additional information compared with what could be obtained in small-scale testing. For example, the EX1 (solid) formulation performed well in the small-scale testing but failed in the medium scale. This provides important information for feeding back into the iterative design loop.

6. Field trials

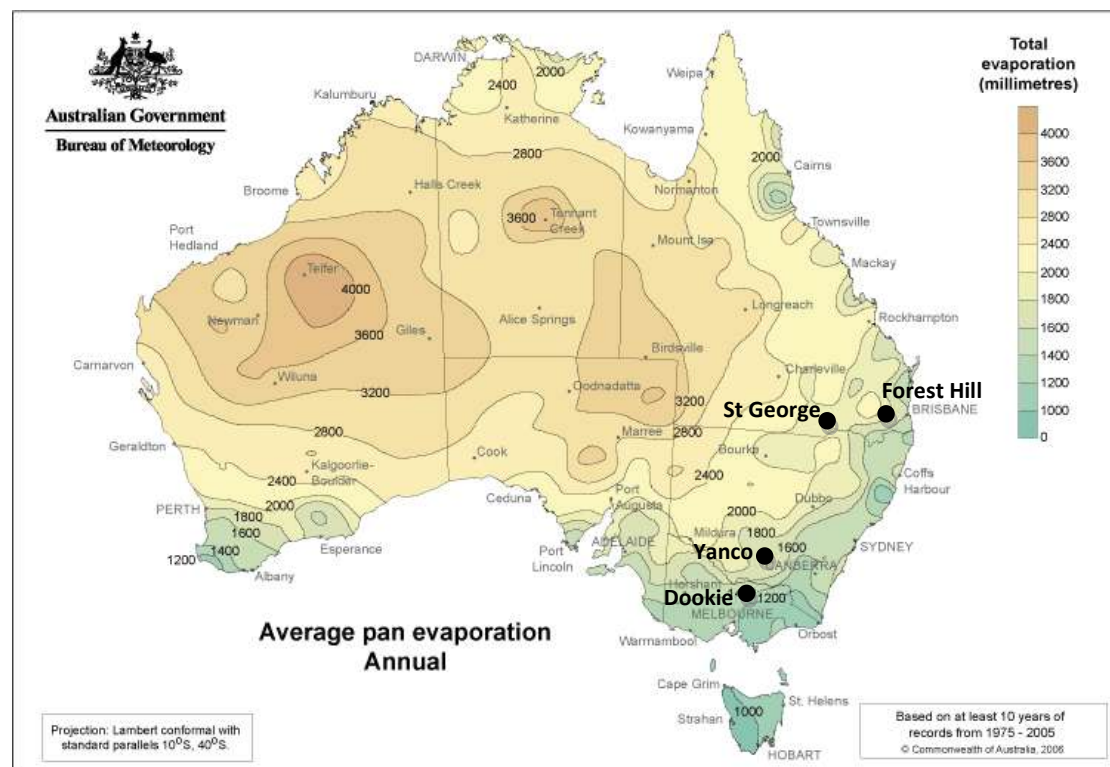
Various field trials in a range of locations tested effectiveness across a variety of Australian climatic and environmental conditions. The trials aimed to:

- determine whether CRC-P technology can be effective in reducing evaporation in an outdoor setting
- test the relative performance of different chemical systems in reducing evaporation to allow selection of the optimal formulation to take to commercialisation
- compare the performance of different physical formulations—solid, suspension and solvent. Information gained from each trial, including performance in reducing evaporation and any observations (e.g. spreading), can be fed back into the design loop to optimise the formulation
- investigate and optimise the application regime—application frequency and dose amount
- begin building a library of suppressant performance information over a range of environmental conditions and locations to assist future development, modelling and commercialisation.

While the general aims, outlined above, were clearly identified before the trials, the specific aims and plans for individual trials were developed immediately before starting work. This meant that the latest information from concurrent laboratory work and any previous field trials could be analysed with conclusions then being applied to the planning. This ensured that each trial was designed as well as possible to provide the desired information, leading to the selection of the most appropriate chemical system, physical formulation and application regime.

The availability of potential testing sites and appropriate personnel were considered when choosing field trial locations. The sites selected were Victoria (Dookie), southern NSW (Yanco) and South East Queensland (Forest Hill and St George). The location of these is shown in Figure 12 along with average evaporation levels across Australia.

Figure 12: Location of field trial sites and average evaporation levels across Australia.

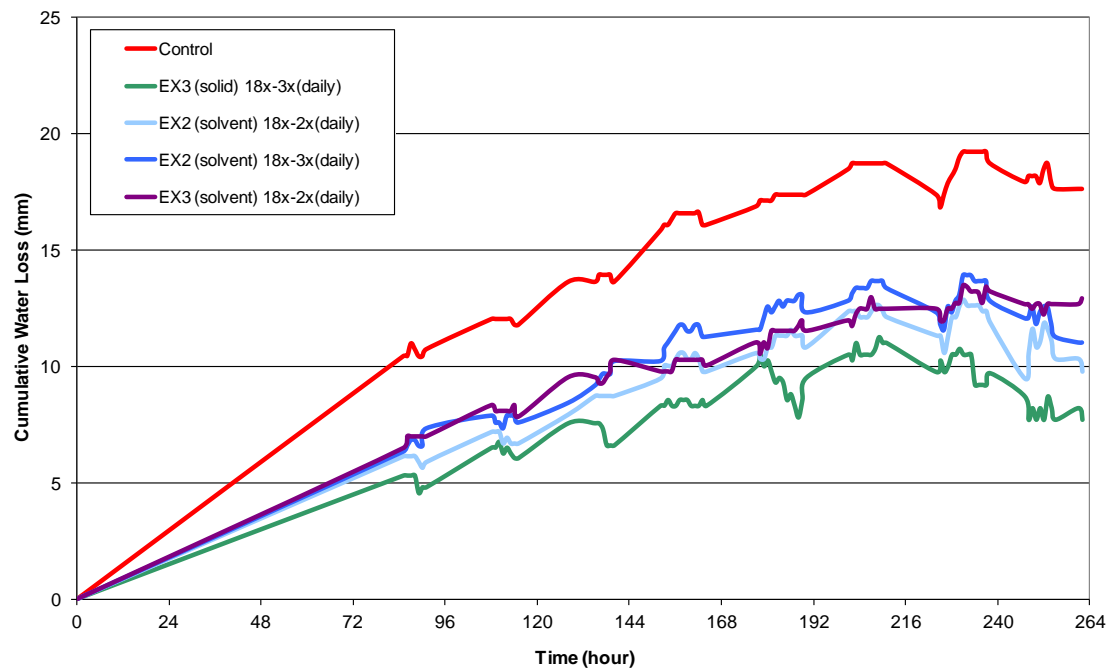


6.1 Data analysis

In the first two field trials at Dookie, Victoria, rulers were used to determine the change in water level over time. Due to the inaccuracy of taking readings only once a day by eye (as discussed in Section 6.2.1.2) all subsequent trials used automatic, data-logging water level sensors. Before being analysed, data was processed to remove interferences from rainfall and diurnal fluctuations. Stronger, less stable weather conditions occurred during the day generating higher amplitude waves, so the night-time water level values were generally used.

To illustrate this, the data for Trial 3 at Yanco (Section 6.3.1.3) is presented below. Figure 13 shows the cumulative water loss (mm) from all channel sections, after data processing described above. Rain periods for the first three days of this trial meant that most of this data was excluded.

Figure 13: Cumulative water loss (mm) from all channels in Trial 3 at Yanco.



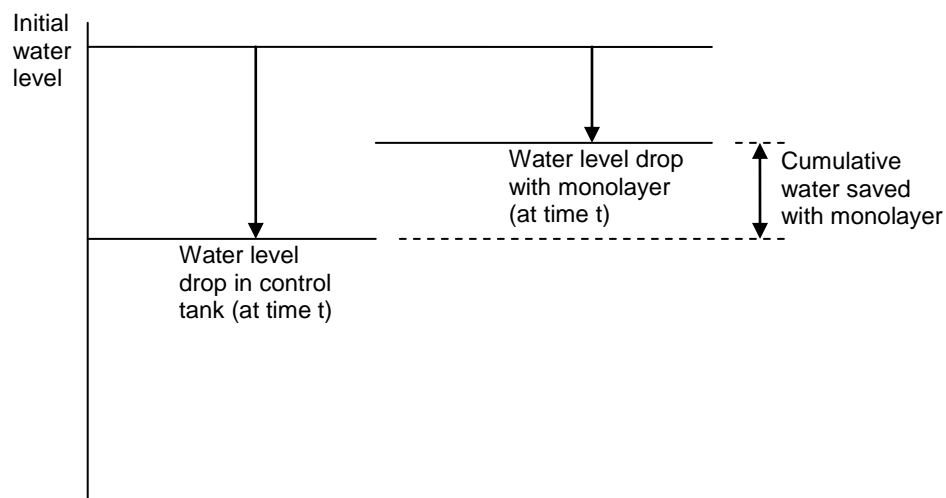
All treated channels lost less water than the control channel indicating all products worked to some extent. The next step in data analysis was to plot the cumulative water saving percentage compared to the control, which at any particular time t , should be:

$$\frac{[(Loss)_{Control} - (Loss)_{Monolayer}]}{(Loss)_{Control}} \times 100$$

Where: $(Loss)_{Control}$ = total water loss of control up to time t
 $(Loss)_{Monolayer}$ = total water loss with monolayer up to time t

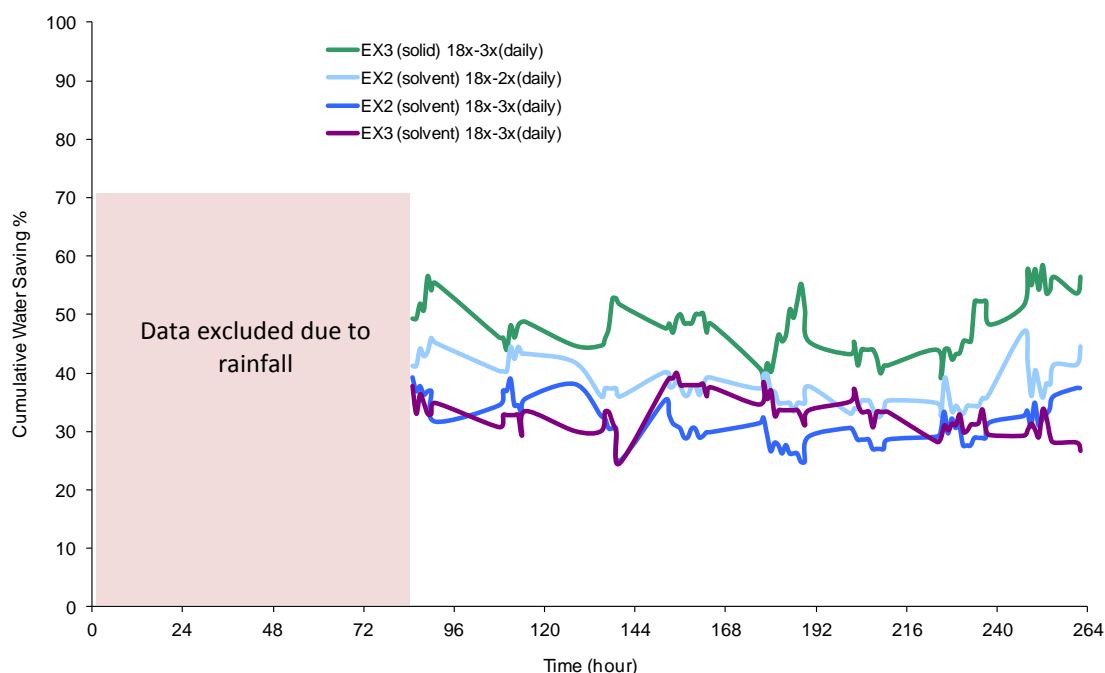
This can also be explained diagrammatically as in Figure 14.

Figure 14: Schematic showing how water savings were calculated for field trials using automatic water level sensors.



For Trial 3 at Yanco the cumulative water saving percentage is shown in Figure 15.

Figure 15: Cumulative water saving percentage of different formulations compared to the control channel for Trial 3 at Yanco.



As the data for the first 72 hours was excluded (due to rain events) the cumulative water savings can only be calculated after this period. The trials show that the cumulative water saving profiles over time are reasonably constant, for example for EX3 (solid) in this trial the sustained water savings over the period from 75 to 265 hours was 50 per cent, with a variation of ± 5 per cent. The solvent formulations all clearly save less water than the solid formulation, however, they all performed similarly, saving 40 ± 5 per cent.

With careful analysis of the data from the automatic water depth sensors and by excluding rain events, reliable data can be obtained from which cumulative water saving percentages can be concluded, generally with an error of ± 5 per cent.

6.2 Dookie, Victoria

The University of Melbourne has a campus at Dookie, 35 km east of Shepparton, where a field trial site was developed. This site was relatively close to the Melbourne-based research team, enabling members to visit and monitor regularly.

Six small troughs (3.7 m^2) and three larger evaporation ponds (135 m^2) were installed at this site and several trials were run.

6.2.1 Small troughs (2010)

The small troughs at Dookie provided the first scaled-up, outdoor testing site for the new surface film technology. The main aim of this site was to provide initial feedback on the performance of various formulations to allow optimisation before undertaking larger-scale field trials. Multiple troughs allowed for several samples to be tested and compared at one time, and under the same climatic conditions, while the small size of the troughs meant only small amounts of each formulation needed to be prepared for this initial field testing.

Six polyethylene troughs (water surface 3.7 m², diameter 2.1 m, height 0.6 m, volume 2000 L) were placed 5 m apart on a cleared patch of earth in April 2010, as shown in Figure 16.

Figure 16: Layout of the six troughs for the first series of small-scale field trials at Dookie. (Photograph: E. Prime)



For the first series of trials in these troughs two 30 cm plastic rulers were glued to the inside of opposite sides of each trough using Dunlop Tile-All Plus—a silane modified polymer adhesive recommended for swimming pools. This product was unlikely to leach into the water due to its single component, water insoluble polymeric system. The water level was then manually recorded from both rulers at 9 am each day of the trial. The two rulers in each trough helped improve accuracy, however, the error involved in measuring the water height using this method was estimated to be ± 1 mm per day from multiple readings taken from the same ruler over a short time. This was caused predominately by the wind making the water level fluctuate.

The troughs were filled with water to a depth of 0.5 m. In between trials more water was added so the troughs would overflow, removing any residual monolayer material.

Dookie campus has an on-site weather station from which rain and evaporation for the previous 24 hours is recorded manually at 9 am each workday. For the first series of trials this data, was used along with temperature and wind information from the Bureau of Meteorology.

6.2.1.1 Trial 1—different water sources (19–27 April 2010)

The first trial on the six troughs was designed to determine whether the novel surface film was effective on water from different sources. Laboratory testing to date had used ultra pure water, or tap water. To be widely effective in the field the product had to work sufficiently well on water from different sources and of differing qualities, potentially including static water (dam) and flowing water (irrigation channels). The trial tested water from three different sources: dam water, river water, and river water treated for domestic use within the Dookie campus. This treatment employed alum to settle suspended clay, flocculation and sedimentation, addition of chlorine, pH adjustment using soda ash solution (which also has the effect of reducing hardness) and passage through a sand filter. Samples of these waters were taken and analysed by EML (Chem) Pty Ltd, with results outlined in Table 3.

Table 3: Water sample analyses for water used in trough Trial 1.

<i>Analyte</i>	<i>Unit</i>	<i>Dam water</i>	<i>River water</i>	<i>Treated water</i>
Total dissolved solids	mg/L	110	220	280
Turbidity	NTU	6.0	36	9.6
pH		8.4	8.5	7.9
Total alkalinity as CaCO ₃	mg/L	77	89	67
Total organic carbon	mg/L	9.8	6.0	4.1
Calcium as Ca	mg/L	12	22	16
Magnesium as Mg	mg/L	6.1	13	4.4
Total hardness as CaCO ₃	mg/L	55	110	57

In general, the dam water was lower in total dissolved solids than the other water types, while the river water had significantly higher turbidity and was considerably harder.

Various application regimes were investigated throughout the field trials. The application regime refers to the amount of product applied (in terms of how many monolayers as described in Section 2.2) and the frequency with which it was applied. In this trial a large initial dose of the evaporation suppressant EX1 (suspension) was applied on day 0 with no subsequent reapplications. The aim was to determine how long a single dose of product maintained efficacy. The details for this trial are shown in Table 4.

Table 4: Trough Trial 1 set-up.

<i>Trough</i>	<i>System</i>		<i>Application regime</i>
1	River water	Control	-
2		EX1 (suspension)	18x monolayers (on day 0)
3	Treated river water	Control	-
4		EX1 (suspension)	18x monolayers (on day 0)
5	Dam water	Control	-
6		EX1 (suspension)	18x monolayers (on day 0)

The average maximum temperature was 27°C for the first four days of the trial, dropping to 18°C for the second four days. The total amount of water lost from the tanks at the end of this trial ranged between 8 and 14 mm. The effect of rain events on days 2, 5 and 8 (total of 12 mm rain) makes it difficult to interpret the results, however, the tanks with the product applied lost less water over the first two days of the trial than the control tanks, with savings of 30–60 per cent observed. After two days this effect was no longer observed. It is unclear whether this was due to the monolayer deteriorating after this time, or the rain event on day two making subsequent results hard to interpret. As a result, this trial was repeated.

6.2.1.2 Trial 2—different water sources (29 April–7 May 2010)

The second trial was a repeat of Trial 1 with the same set-up used as shown in Table 4. There were no significant rain events throughout the second trial and the maximum temperature was around 20°C over the duration of the trial.

The total amount of water lost from the tanks at the conclusion of this trial ranged between five and 20 mm. All tanks lost 1–2 mm of water daily, the accurate reading of which is likely to

be within human error (as described in Section 6.2.1). Savings observed were around 60 per cent for the dam water, 30–40 per cent for treated water and 20–30 per cent for river water, however, given the error inherent in reading the water depth and the low levels of evaporation, these figures are unreliable.

These two trials demonstrated that, as expected, the EX1 suspension product performs similarly on water from different sources, including untreated river water, dam water and treated water. Savings were around 30–60 per cent, compared to the water lost in the control troughs. The product performed best over the first two to three days after being applied. Some inaccuracy is expected in the results due to the relatively low levels of evaporation observed for this time of the year, generally about 1–2 mm per day according to data obtained from the weather station at Dookie campus. As a result, no further trials were carried out in these small troughs until the following summer (2010–11). It was also concluded from these trials that taking a single daily water depth reading by eye from a ruler attached to the side of the troughs was not a sufficiently accurate way to obtain water loss data. The human error involved in this method was too large to provide reliable results. As a result a more sensitive method for measuring water loss was sourced and used in subsequent trials.

6.2.2 Small troughs (2011)

In 2011 the six water troughs (water surface 3.7 m²) were transported to a new testing area at Dookie as shown in Figure 17 (shown alongside the new larger evaporation ponds described in Section 6.2.3).

Automatic water depth measuring devices (Odyssey's capacitance water level sensor probe with an interval accuracy ± 1 mm shrouded in a slotted PVC tube, recording at 10 minute intervals) were installed as shown in Figure 18. The PVC slotted shroud can shield the water around the probe from wind-induced wave action, making the system more accurate. Taking regular readings over the length of the trial also improved accuracy.

Figure 17: New layout of the six troughs for Trial 3 onwards (shown alongside the three large evaporation ponds). (Photograph: A. Leung)



Figure 18: Odyssey's capacitance water level sensor probe and the PVC shroud installed in the evaporation ponds and water troughs. (Photograph: A. Leung)



6.2.2.1 Trial 3—different physical formulations (8–15 February 2011)

The first trial using the automatic water level sensors took place in February with the set-up and application regime for the troughs outlined in Table 5. The aim of this trial was to test various physical formulations such as solids with/without additives (to improve the physical properties), and a suspension (10 wt%). Product was applied every three days as it was found in the first series of trials in the troughs that the performance started to deteriorate after that time. For these trials the troughs were filled with untreated water direct from the river system, and ran for seven days.

Table 5: Trough Trial 3 set-up.

<i>Trough</i>	<i>System</i>	<i>Application regime</i>
1	Control	-
2	EX3 (solid)	18x monolayers (every 3 days)
3	EX1 (solid) 1	18x monolayers (every 3 days)
4	EX1 (solid) 2	18x monolayers (every 3 days)
5	EX3 (suspension)	18x monolayers (every 3 days)

The weather was warm over this period with an average daily maximum of 27°C. However, significant rain events on days two and three (total 48 mm rain) disrupted the measurements and made it difficult to interpret the results. Analysing the data as described in Section 6.1, did show that the solid powders based on EX1 both saved considerably less water than the solid and suspension, based on EX3 (10–15% compared to 30–35%), indicating that EX3 is superior to EX1.

6.2.3 Large ponds

To further test the evaporation control system, field trials were carried out on larger bodies of water. Three evaporation ponds were set up using commercial above-ground oval swimming pools (18 x 7.5 m) and installed at Dookie as shown in Figure 17 above, and Figure 19 below. Each pond has a surface area of about 135 m² and a height of 1.32 m.

One pond was used as a control while the other two tested two formulations in identical conditions, making them directly comparable. It can be difficult to compare results across different trials given diverse climatic conditions during each trial period.

Figure 19: Large evaporation ponds installed at Dookie. Each pond has a surface area of 135 m². (Photograph: A. Leung)



The same automatic water depth measuring devices that were installed in the troughs were also put into the three ponds. A blank trial using these sensors was carried out initially to ensure all ponds lost water at the same rate, and that the sensors were accurate.

On the day before the trial started, the three evaporation ponds were filled with untreated river water to the same height (20 cm from the top, approximately 1.3 m deep). In between trials the ponds were cleaned by flooding with fresh river water, meaning any residual material on the surface would be drained out from the skimmer box overflow (positioned near the top of the pond). Product was applied to the upwind side of the ponds by hand.

6.2.3.1 Trial 1—different chemical systems (1–15 March 2011)

The first trial looked at the suspension formulation (10 wt% solid loading) with two different products tested. The application regime for this trial was deliberately designed to have a higher initial dose (18x) to clean the water surface and establish a good film. Subsequent applications were then at a lower rate (6x) to maintain the film coverage at a more economically viable cost. The trial was run for two weeks (14 days). The different treatments used in the evaporation ponds for Trial 1 are shown in Table 6.

Table 6: Evaporation ponds Trial 1 set-up.

Pond	System	Application regime	
		Initial	Subsequent
1	Control	-	-
2	EX3 (suspension)	18x monolayers	6x monolayers (every 3 days)
3	EX1 (suspension)	18x monolayers	6x monolayers (every 3 days)

The weather was warm throughout this trial with an average daily maximum of 26°C, and only two periods of rain towards the end of the trial (total 25 mm). Excluding the rain-affected days, the overall result showed that EX3 (suspension) formulation had water savings of 50–60 per cent ($\pm 5\%$ as described in Section 6.1), whereas EX1 (suspension) formulation showed negligible water saving. This correlates well with the results found in Trial 3 in the small troughs where formulations based on EX1 showed a much lower water saving level than formulations based on EX3. In both these trials EX3 (suspension) showed promising performance.

The trial also revealed that the regime of applying a large dose initially followed by reapplication at lower levels (6x) was enough to maintain a surface film capable of reducing evaporation.

6.2.3.2 Trial 2—different reapplication dose (8–22 April 2011)

Trial 2 looked at the effect of the different reapplication dose (6x) used in Trial 1 with good results, when using EX3 as a solid. The details for this trial are shown in Table 7.

Table 7: Evaporation ponds Trial 2 set-up.

Pond	System	Application regime	
		Initial	Subsequent
1	Control	-	-
2	EX3 (solid)	18x monolayers	6x monolayers (every 3 days)

The weather was significantly cooler during this trial with the average maximum temperature of only 19.5°C, meaning lower evaporation. A total of 35 mm of rain fell at the start of the trial.

The EX3 (solid) formulation was shown to have an evaporation mitigation effect of around 50 per cent water saving with the new application regime of an initial dose of 18x and subsequent doses of 6x every three days. This result is comparable to that obtained from the EX3 (suspension) formulation under the same application regime in Trial 1 (50–60%), although it is difficult to directly compare these results due to differences in climatic conditions across the two trials.

6.3 Yanco, New South Wales

Yanco Agricultural Institute (YAI) is part of the NSW Department of Primary Industries and is located between Leeton and Narrandera in the Murrumbidgee Irrigation Area. The site has previously been used by the CRC for Irrigation Futures (CRC-IF) for trials on evaporation mitigation products and therefore the staff had established capability and experience in

carrying out these tests. Lined sections of an old irrigation channel were used to test the products.

6.3.1 Water channels

Five sections of an old irrigation channel were created (water surface of ~220 m²) and each lined with a single piece of polypropylene to eliminate seepage, as shown in Figure 20. The liner is held in place by the water in the pond, and secured at the edges above the water level using nails.

Figure 20: Lined sections of an old irrigation channel at Yanco Agricultural Institute.
(Photograph: A. Leung)



Automatic water depth measuring devices (Odyssey's capacitance water level sensor probe logging every hour) were installed. A blank trial was run to ensure the accuracy of the sensors and the integrity of the linings to prevent seepage. From this blank trial all channels were shown to have consistent water losses indicating that seepage was not an issue. For all trials the channels were filled with untreated water from a nearby flowing irrigation channel. Between trials the channels were emptied, the liners scrubbed, and then refilled with fresh water from the nearby irrigation channel.

6.3.1.1 Trial 1—different chemical and physical formulations (28 February–30 March 2011)

This 30-day trial compared the solid and suspension formulations of EX1 and EX3. Details of the samples tested are shown in Table 8. The suspension was 10 wt% solid loading.

Table 8: Water channel Trial 1 set-up.

<i>Channel</i>	<i>System</i>	<i>Application regime</i>
1	EX3 (solid)	18x monolayers (every 3 days)
2	EX1 (solid)	18x monolayers (every 3 days)
3	EX3 (suspension)	18x monolayers (every 3 days)
4	EX1 (suspension)	18x monolayers (every 3 days)
5	Control	-

The average daily maximum during the trial period was 26°C, with many small rain events bringing 66 mm of rain over the month. Despite the rain, all the tested formulations were able to save water from evaporation to some extent. The solid and suspension formulations based on EX1 saved 10–20 per cent while those based on EX3 saved 20–30 per cent. Savings were lower than those generally obtained in trials run at Dookie during similar time periods. This could be due to a number of factors including: the rain events which occurred throughout this trial, the larger scale of these water surfaces compared with Dookie, and other differences inherent between the two locations, such as weather, water quality and spatial configuration. The impact of these factors may be narrowed down following many further field trials at various locations, allowing a library of performance information and conditions to be built. However, it was found during this trial that formulations made from EX3 perform better than the same formulation made from EX1, agreeing with results obtained during the Dookie trials.

6.3.1.2 Trial 2—different reapplication doses (13 April–3 May 2011)

A second trial was run in April 2011 for 14 days to investigate the effect of various application regimes for the EX3 solid formulation. The initial dose of 18x monolayers was maintained while subsequent application amounts were reduced to 2, 3 or 6x monolayers every three days. A solvent formulation was also included for comparison because to-date this had been the best performing system and was therefore the benchmark. The details of samples and application regime used in Trial 2 are shown in Table 9.

Table 9: Water channel Trial 2 set-up.

<i>Channel</i>	<i>System</i>	<i>Application regime</i>	
		<i>Initial</i>	<i>Subsequent</i>
1	EX3 (solid)	18x monolayers	2x monolayers (every 3 days)
2	EX3 (solid)	18x monolayers	6x monolayers (every 3 days)
3	EX3 (solid)	18x monolayers	3x monolayers (every 3 days)
4	EX3 (solvent)	18x monolayers	3x monolayers (every 3 days)
5	Control		-

The average daily maximum temperature for this trial was 22°C with no rain falling throughout the exercise. The products all worked well with savings generally ranging from 20 to 50 per

cent during the trial. All samples appeared to perform similarly, indicating that topping up with a small amount of fresh product after a large initial dose, was sufficient to maintain the performance of the surface film. Subsequent trials will now generally focus on using an application regime that involves smaller reapplication amounts.

6.3.1.3 Trial 3—different reapplication frequency (11–25 May 2011)

A third trial was run for 14 days in May 2011. This trial focused on the solvent formulation and looked at increasing the frequency of reapplications as well as the effect of using EX2 compared with EX3. Following the discovery in Trial 2 that reapplying lower amounts of product was more effective than reapplying large doses, these application doses were used in this trial with applications reapplied daily instead of every three days. The details are shown in Table 10.

Table 10: Water channel Trial 3 set-up.

Channel	System	Application regime	
		Initial	Subsequent
1	EX3 (solid)	18x monolayers	3x monolayers (daily)
2	EX2 (solvent)	18x monolayers	2x monolayers (daily)
3	EX2 (solvent)	18x monolayers	3x monolayers (daily)
4	EX3 (solvent)	18x monolayers	3x monolayers (daily)
5	Control	-	-

The weather was cooler in late May with an average daily maximum of 17°C. A total of 25 mm of rain fell during this trial with 19 mm recorded on one day late in the process.

These trials showed good results (as seen in Figure 13 and Figure 15), with EX3 (solid) saving 50 ± 5 per cent, similar to the savings obtained in the Dookie trials, and the solvent products all saving 40 ± 5 per cent. Reapplying a lower amount daily successfully maintained good evaporation suppression. There seemed to be no difference between reapplying EX2 (solvent) at 2x or 3x reapplication dose. This was an encouraging result, as it meant that less product may be needed to achieve the same water saving.

6.3.1.4 Trial 4—different application regimes (1–13 July 2011)

A fourth trial was conducted in the water channels in July 2011. This trial used the same sample, EX3 (solvent), in three channels. Different application doses, both initial and subsequent, were tested to determine the most effective regime for obtaining high water evaporation savings. The solid powder was used in channel 1 as a comparison. The sample and application regime details for this trial are shown in Table 11.

Table 11: Water channel Trial 4 set-up.

Channel	System	Application regime	
		Initial	Subsequent
1	EX3 (solid)	18x monolayers	3x monolayers (daily)
2	EX3 (solvent)	18x monolayers	3x monolayers (daily)
3	EX3 (solvent)	1x monolayer	1x monolayer (daily)
4	EX3 (solvent)	2x monolayers	2x monolayers (daily)
5	Control	-	-

As this trial was carried out in the winter months, the cooler weather (average daily maximum of 14°C) meant lower evaporation rates overall. Several small rain events brought a total of 10 mm.

The trial showed that if the product was applied at 1x monolayer initially and subsequently (channel 3), then the product did not work at all, with zero water savings. However the larger dosage regimes, 2x and 18x initially, work similarly to each other and to the solid formulation. The large rain interruptions made it difficult to draw quantitative conclusions from this work, so a large amount of data was excluded from analysis. Low levels of evaporation during this period also magnified errors. Further trials to obtain the optimum application regime will take place once the weather has improved in late spring/summer 2011–12.

6.4 Logan's dam, Forest Hill, Queensland

This section summarises the activities, observations and results relating to a series of large-scale field trials held at Logan's dam in the first half of 2011. The trials evaluated a water suspension product made from evaporation suppressant EX1 and were carried out by the University of Melbourne, the University of Southern Queensland (USQ), the University of Queensland (UQ) and CSIRO.

6.4.1 Field trial site

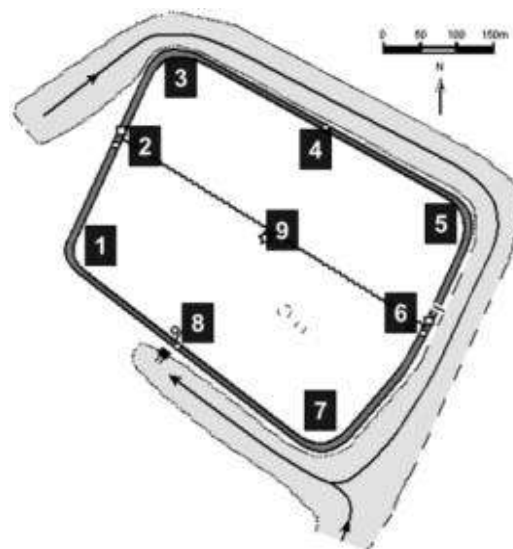
The field trial site was Logan's dam, a 16 ha body of water near the town of Forest Hill (near Gatton) in the Lockyer Valley south-west of Brisbane. This site was used because previously it had been instrumented for measuring evaporation losses by a collaborating team of scientists from CSIRO, UQ and USQ (McJannet et al. 2011).

6.4.2 Trial methods

The evaporation suppressant used in the trial was a 10 wt% suspension of EX1 in water. At the time of this trial it was considered to be the most commercially viable option with production capable of being scaled up to the levels of product needed to carry out this exercise.

Product was applied in equal amounts to the water surface by hand at a minimum of three positions on the upwind side of the prevailing wind. Figure 21 shows the location of the nine possible addition sites at Logan's dam. Positions one to eight were used for adding the evaporation suppressant by hand.

Figure 21: The position of nine possible addition sites at Logan's dam.



The team from CSIRO measured evaporation using both scintillometry and eddy covariance methods. These techniques meant that evaporation could be measured directly from a water storage area, rather than relying on the presence of a control dam, or using indirect methods such as pan evaporation or meteorological data.

A scintillometer measures small fluctuations in the refractive index of air, which are then used to determine the sensible and latent heat fluxes (the transfer of heat between the surface and the air). Adding information about air temperature, humidity and wind speed, means that evaporation can then be calculated.

Eddy covariance is a complex statistical method of determining evaporation. It relies on correlating fast fluctuations of vertical wind speed with those in atmospheric water vapour density.

Further details on these methods can be found in McJannet et al. (2011).

6.4.3 Results

6.4.3.1 Visual observations of spreading

When the evaporation suppressant was added, its presence and spreading could be seen because the suppressant changes the surface tension, attenuating waves and flattening the surface of the water. Figure 22 shows the suppressant advancing across the surface of the water towards the back of the dam. Where the suppressant was present (foreground) the surface was smoother and reflected the sky. Beyond the advancing front of the suppressant, the water was more affected by surface waves. As the applied material spreads further to cover the entire surface in about an hour, the layer becomes thinner and therefore increasingly difficult to determine the presence of the film by eye. Methods such as placing a drop of indicator oil on the water surface and observing whether it forms a droplet or spreads, can then be used to measure the surface tension and therefore whether surface film is present or not.

Figure 22: An advancing front of suppressant from the foreground towards the back of Logan's dam shown by the smooth water surface in the image. (Photograph: G. O'Shannassy)



It was observed that when the material was being applied, wind and surface current movements at the time strongly influenced its spread to form the initial surface film. This information could be useful when programming an automatic application system to distribute the product across a water surface.

6.4.3.2 Evaporation suppression

The best result over these trials came from the experiment held on 29 March 2011 when a large dose of the evaporation suppressant reduced evaporation by 38 ± 5 per cent relative to the preceding day when climatic conditions (e.g. wind speed, temperature) were essentially identical. Figure 23 shows the level of water lost over these two days measured using the eddy covariance method. Figure 24 is an image of the dam taken during the trial on 29 March 2011 and shows its surface was well covered with the suppressant (smooth, reflective surface). Indicator oils were used to take surface pressure measurements at various locations at 6 am on the 30 March. They showed significant monolayer was present across the dam (approximately 60% coverage). This indicates that this formulation is capable of maintaining good surface coverage the day after application, despite probable disruption by wind, surface currents and birds.

Figure 23: The level of water lost to evaporation, measured by eddy covariance, on two successive days under essentially identical evaporation conditions. The dose of evaporation suppressant applied on the second day (29 March) was much larger.

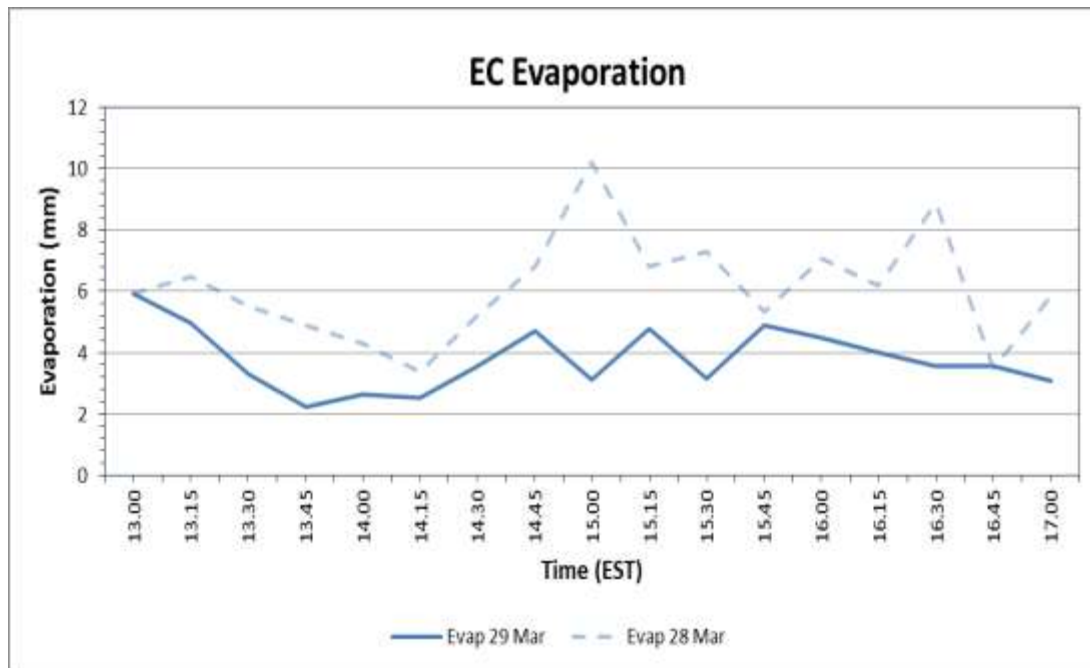


Figure 24: An image of the dam taken during the trial on 29 March 2011. It shows a smooth surface across the dam indicating the surface of the dam is well covered with the suppressant. (Photograph: G. O'Shannassy).



6.4.4 Conclusions

The Logan's dam trials demonstrated promising performance with an evaporation saving of 38 ± 5 per cent observed in one trial. However, they also showed that formulating the product as a suspension in water was problematic due to: difficulties in scaling up production and issues with product stability and shelf life. Future product development should focus on providing the evaporation suppressant as a solid, which will have a much longer shelf life and can be more easily formulated, transported, handled and dispensed.

The small-scale field trials showed that evaporation suppressants EX2 and EX3 performed consistently better than EX1. As a result, all further product development and testing will be based on these suppressants.

6.5 St George, Queensland

St George is located in southern Queensland, 500 km inland from Brisbane, and is a region with a strong agricultural base. Large-scale field trials will be undertaken at this site over the summer of 2011–12 using three dams of about 12 ha each.

6.5.1 Dams

The three dams have been selected based on a range of selection criteria:

- similar in size
- located close together to minimise location variations
- low likelihood of the farmer needing to use water from the dams over the summer period
- uniformity of dam shape and surrounding vegetation.

Photos of two of the three dams are shown as Figure 25.

Figure 25: Two of the three dams selected for large-scale field trials at St George, Queensland. (Photographs: A. Leung).





The USQ team took background readings of evaporation and seepage from the three selected dams over the summer of 2010–11 using pressure sensitive transducers to monitor the water depth over time (Craig et al. 2007). Seepage was minimal compared with evaporation rates and the three dams all had similar seepage levels, making them ideal for evaporation studies.

Two types of depth sensors (pressure sensitive transducers and capacitance) were installed (two of each) in each dam to provide data on the changing water depth. Also an automatic weather station was installed to provide data on environmental conditions throughout the trial.

Trials at St George will be undertaken using the approach to experimental design outlined in Section 2.6 and the beginning of Section 6. An overall general plan for the trials will be developed initially, however, for each specific trial the latest information from laboratory, small-scale field trials, any previous St George trials and modelling will be analysed and conclusions from these applied to the planning.

This will ensure that each trial is designed as well as possible to provide the desired information, with the most appropriate systems being chosen. This may or may not include the application regime, the chemical system and formulation used, the possible use of automatic applicators and the location of application points across the dams.

6.6 Field trial conclusions

Evaporation savings of 40–60 per cent have been observed from the field trials carried out at Dookie, Yanco, and Logan's dam using the novel evaporation suppression products. The error determined during data analysis was found to be five percentage points.

Further conclusions that can be drawn from the field trials are:

- Two small-scale field trial options set up in two locations ran smoothly: six identical small troughs (3.7 m²), three identical ponds (135 m²) at Dookie, Victoria, and five lined channel sections (220 m²) at Yanco, NSW. Several trials were carried out across these sites throughout the project, with results showing that evaporation savings of 40–60 per cent are obtainable.

- Two large-scale field trial options were set-up. Trials were conducted out at Logan's dam in Qld (16 ha), while the second site with three dams at St George, Qld (12 ha) was set-up with trials starting January 2012. The results from Logan's dam demonstrated that an evaporation saving of 38 ± 5 per cent was achieved from a product based on EX1.
- A wet and cool summer in 2010–11 made interpreting field trial results difficult as rain events occurred in almost every trial. Also the cooler weather meant evaporation levels were lower than normal, so the savings obtained with the surface film product were hard to detect and measure.
- Formulations based on EX1 demonstrated moderate water savings in the smaller field trials. However, their effectiveness significantly reduced when they were tested in larger sized water bodies. Therefore EX2 and EX3 are the preferred products for future development.
- The method used to formulate the product affects the results, with the solvent and solid formulation generally showing superior results to the suspension. As the solvent system is unlikely to be commercially acceptable, work is focusing on the solid formulation for future development.
- The application regime used had a large effect on the results. The preferred regime was found to be a larger initial dose (18x monolayers) followed by a daily reapplication of a smaller amount (2–3x) which would maintain surface coverage and suppress evaporation.

From the extensive field trial work carried out, the formulation that will be the focus of further development as the most likely commercial product is EX3 (solid). However, further field work is needed to fully understand the performance of the system and to optimise the formulation.

7. Product deployment

An applicator is needed to provide a cost-effective way to distribute the surface film material over the water surface. The type of applicator will depend on the formulation used, whether solid powder or liquid suspension. Initial work has investigated a range of options. An application system also needs to have applicators located at optimal positions and programmed to give the best coverage of the water surface. Initially modelling the system is the best way to understand the best dispensing protocol.

7.1 Solid applicator

A commercially available dispensing system, designed by a local Melbourne engineer for applying WaterSavr® (a solid powder monolayer system described in Section 2.2.1) onto the water surface, has been identified and purchased, and is shown in Figure 26. The applicator is capable of being programmed to dispense specific amounts of material at certain times. It is solar powered with a back-up battery supply. The system will be trialed with the EX3 solid powder formulation in the summer of 2011–12.

Figure 26: Solid application system identified and purchased. (Photograph: Osprey Pty Ltd).



7.2 Liquid applicator

In the case of a suspension product, a different type of dispensing system would be required. The CRC for Irrigation Futures (CRC-IF) and the National Centre for Engineering in Agriculture (at USQ) have developed a smart application system to use with liquid evaporation suppressant products. The dispensing units have been developed to allow dosage at a prescribed rate and frequency, and the system is designed for autonomous operation. Atmospheric sensors and a coordinator unit can be used to analyse and implement appropriate dispensing decisions (Brink et al. 2009 & 2011).

Once the final physical formulation is optimised, work will progress to extensive testing and optimising the appropriate delivery system.

7.3 Modelling

Modelling the application of product to the water surface can be used to develop the best strategy for applying it including identifying where the applicator should be located and protocols for dispensing the product. The National Centre for Engineering in Agriculture, USQ conducted a modelling study to look at these issues.

The objective of the study was to estimate (at a first approximation) the optimal number and arrangement of applicators, plus the application rate and duration required to most ensure a high degree of surface coverage of the monolayer surface on three square storages (50 m x 50 m; 500 m x 500 m; and 5 km x 5 km) which was also cost effective.

The modelling considered data on historical wind speed and direction frequency intervals for two sites, a low wind site (Mungindi, NSW) and a high wind site (Scoresby, Victoria). The outputs were: coverage achieved, application rate, time to reach a steady state, and coverage maps. An example result for a 5 km x 5 km storage at Mungindi showed that if 121 applicators were used (arranged in a 11x11 grid with 500 m between) and product was applied at a certain rate over six hours then 40 per cent of the surface could be covered for 40 per cent of the time. If 441 applicators are used (in a 21x21 grid with 250 m between) with the same application rate and time then 97 per cent of the surface could be covered 90 per cent of the time. However, in the latter case approximately three times the amount of product was required compared with the 11x11 grid, increasing the cost of achieving this high level of coverage. The final application strategy will therefore be a trade-off between the cost and maintenance of extra applicators and product, and the value of extra water that could be saved.

As the final chemical and physical formulation of the evaporation suppressant is refined throughout the field trials and other testing, further information on its characteristics such as spreading rate will be determined and fed back into the developed application model. This will enable the model to be tweaked to provide more accurate information on the best application strategy for the selected product.

8. Environmental testing and approvals

Before these chemical films can be commercialised, appropriate environmental testing needs to be carried out to ensure they have no negative impacts. A testing regime has been developed to examine toxicity and ready biodegradability.

The contents of the evaporation control product currently under development are widely and commonly used in products including those involving human exposure, such as detergents and cosmetics. They are well-known products for which there is considerable publically available data. All components of the product are currently used within Australia and are listed on the Australian Inventory of Chemical Substances. The product does not fall under the definition of an Ag & Vet chemical, meaning it is not subject to regulation under the *Agricultural and Veterinary Chemicals Act 1994*. This product could also be used on potable water storages—the regulation of drinking water falls under state jurisdiction. Therefore relevant state departments will be kept informed of the project's progress.

8.1 Toxicity testing

A National Association of Testing Authorities (NATA) accredited independent laboratory has tested the toxicity of this product using internationally accepted methods. The tests have been conducted to evaluate the toxicity on three standard environmental indicator species: *Ceriodaphnia* (water flea), fish (rainbow fish) and algae.

If the product was applied to a water body that was 1 m deep, at a dose of 18x monolayers, the highest dose tested in field trials; then the concentration would be 0.45 mg/L. In toxicity testing, the lowest observed effective concentration (LOEC) is the concentration of material that induces a response in the species. For all three indicator species the LOEC was found to be considerably higher than the expected concentration in the water body, 0.45 mg/L. This indicates that the evaporation suppressant exhibits low toxicity and suggests that the product will be suitable for its intended use as an ultra-thin film used to suppress evaporation on water bodies.

8.2 Ready biodegradability

Ready biodegradability testing measures how long the substance takes to degrade under standard conditions. Substances are considered to be readily biodegradable if CO₂ production exceeds 60 per cent of the theoretical maximum within 28 days and if this level of CO₂ production is attained within ten days of degradation exceeding 10 per cent. The testing protocols used have been developed by the Organization for Economic Cooperation and Development (OECD) and are currently considered the world standard for ready biodegradation studies. The evaporation suppressant is currently undergoing ready biodegradability testing. However, previous studies on a similar monolayer-forming compound, 1-octadecanol, concluded that it was considered to have ready biodegradability with 67 per cent of the material disappearing after 28 days (UNEP 1995).

8.3 Environmental report

An independent toxicologist has prepared a draft dossier to review the literature, toxicity and ready biodegradability results and to evaluate the use of the evaporation control product in water intended for agricultural and potable use. The draft report concluded that the

components within the product are rapidly biodegradable and exhibit low toxicity. A final report will be prepared once results from the ready biodegradability testing are received.

9. Economic analysis

Economic analysis is a useful tool as it can inform the end-user whether there is value in applying an evaporation suppressant. Product would be applied if the value of the water saved exceeded the cost of saving the water.

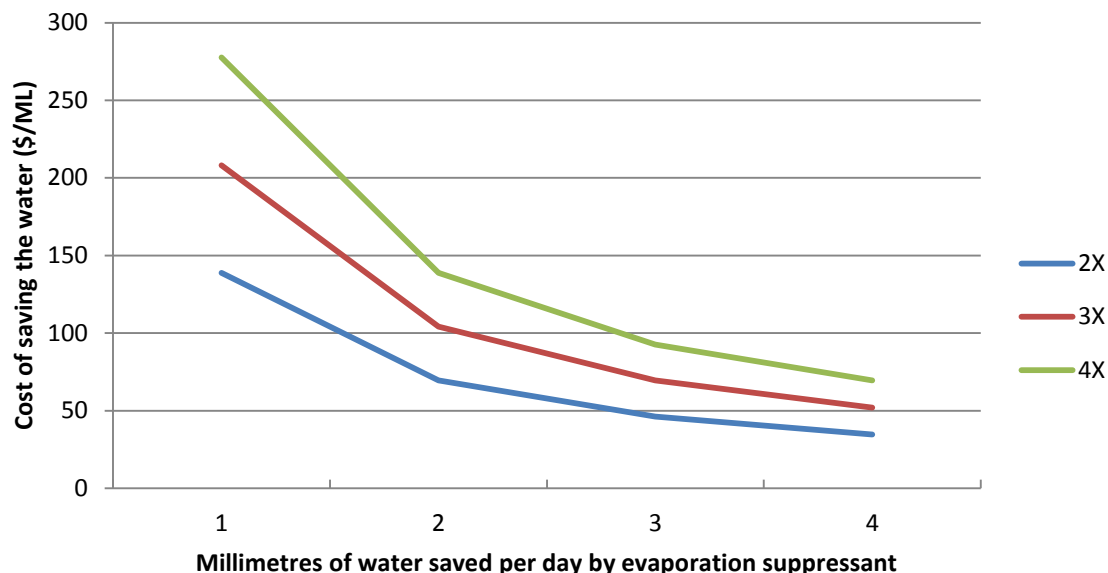
9.1 Cost of saving water

To determine the economic benefits the following assumptions have been made:

- after initial application, the product is reapplied once a day in the range of 2x to 4x monolayers (the application rates looking most promising in field trials to date)
- product pricing has been reasonably estimated based on current chemical manufacturing price information
- the cost of saving the water (\$/ML) equals the cost of buying the suppressant product. Capital costs are not included in this analysis as they are difficult to estimate at this stage, however they are anticipated to be low and are dependent on how each individual end user chooses to manage the system.

A graph showing the cost of saving the water versus the millimetres of water saved from evaporation per day for different daily application rates is shown in Figure 27.

Figure 27: Plot of the cost of saving the water in \$/ML versus the millimetres of evaporation suppressed for daily addition of three different levels of monolayers.



This analysis considers the cases of evaporation savings of 1, 2, 3 and 4 mm/day. For example if the evaporation suppressant is 50 per cent effective and is applied once a day when the evaporation rate is 6 mm/day then the water saved by the suppressant is 3 mm/day. If evaporation rates are lower, at 2 mm/day, then the water saved is 1 mm/day.

The analysis shows that the product provides benefits for savings of 1 mm/day for the following combinations of water saving costs and daily addition rates:

- \$138/ML for 2x application

- \$208/ML for 3x application
- \$278/ML for 4x application.

For savings of 3 mm per day the corresponding combinations of water saving costs and daily addition rates are:

- \$46/ML for 2x application
- \$69/ML for 3x application
- \$93/ML for 4x application.

Therefore if the end-user values the saved water at a level higher than this cost they may consider it beneficial to use the product.

9.2 Water market analysis

Australian water allocation trading prices can vary dramatically across seasons and locations depending on the weather, rainfall and other factors. Table 12 shows the average allocation trading prices for the southern connected Murray–Darling Basin, the main connected water market in Australia, over the past four seasons (National Water Commission 2008–11).

Table 12: Average water allocation trading prices for the southern connected Murray–Darling Basin over recent years.

<i>Season</i>	<i>Average trading price (\$/ML)</i>
2007–08	650
2008–09	350
2009–10	150
2010–11	32

Combining the information from Figure 27 and Table 12 shows that in some years the average water trading price is well above the highest water saving costs. However, in other years the average water trading price is considerably lower. The end user therefore needs to take into account their position and the value of water to them before deciding whether to use the evaporation suppressant product at a particular time.

10. Commercialisation plan

Large-scale field trials will be carried out as described in Section 6.5 for St George. If successful results are obtained in these trials an extended series of large-scale field trials will be conducted in different locations around Australia. This will determine whether the technology works at a large scale, in various locations, and in a range of environmental conditions.

If necessary further development work will continue to optimise the physical formulation with laboratory studies being undertaken on any improved formulations. These would then continue through the small and medium field trials before progressing to the large-scale trials.

If satisfactory results are obtained in the planned large-scale field trials then an evaporation suppressant product will be made available to selected end users in 2012–13. These may be end users who have been involved in field trials of this, or previous monolayer products. They may also be end users who have a relationship with project partners and have demonstrated an interest in the evaporation suppressant product.

If continuing field trials demonstrate sufficient water savings, then a more rigorous economic analysis and detailed marketplace evaluation would be undertaken. A commercial product based on this research may then be developed.

11. Glossary

Monolayer	An extremely thin (one molecule) film formed at the air/water interface.
18x, 6x	Different application amounts, equivalent to 18 or 6 times the amount needed to completely cover the water surface with one monolayer.
Ready biodegradability	The degradability of a compound under standard conditions. Substances are considered to be readily biodegradable if CO ₂ production exceeds 60 per cent of the theoretical maximum within 28 days and if this level of CO ₂ production is attained within ten days of degradation exceeding 10 per cent.

12. Bibliography

- Barnes GT & La Mer VK 1962, 'Laboratory investigation and evaluation of monolayers for retarding the evaporation of water', *Retardation Evaporation Monolayers*, papers symposium, New York, NY, pp. 35–39.
- Barnes GT 1993, 'Optimum conditions for evaporation control by monolayers,' *Journal of Hydrology*, 145(1–2):165–173.
- Barnes GT 1997, 'Permeation through monolayers', *Colloids and Surfaces Part A: Physiochemical and Engineering Aspects*, 126(2–3):149–158.
- Barnes GT 2008, 'The potential for monolayers to reduce the evaporation of water from large water storages', *Agricultural Water Management*, 95:339–353.
- Brink GN, Symes TW, Pittaway PA, Hancock NH, Pather S & Schmidt E 2009, "Smart" monolayer application and management to reduce evaporation on farm dams—formulation of a universal design framework', *Proceedings of the Environmental Research Event*, Noosa Qld, pp. 1–10.
- Brink GN, Symes TW & Hancock NH 2011, 'Development of a smart monolayer application system for reducing evaporation from farm dams: introductory paper', *Australian Journal of Multi-disciplinary Engineering*, 8(2):121–130.
- Bureau of Reclamation 1962, 'Water loss investigations: Lake Cachuma—1961 evaporation reduction investigations', *Chemical Engineering Laboratory Report no. S1-33*, US Bureau of Reclamation, Denver.
- Craig I, Green A, Scobie M & Schmidt E 2005, 'Controlling evaporation loss from water storage', *NCEA Publication No. 1000580/1*.
- Craig I, Aravinthan V, Baillie C, Beswick A, Barnes G, Bradbury R, Connal L, Coop P, Fellows C, Fitzmaurice L, Foley J, Hancock N, Lamb D, Morrison P, Misra R, Mossad R, Pittaway P, Prime E, Rees S, Schmidt E, Solomon D, Symes T & Turnbull D 2007, 'Evaporation, seepage and water quality management in storage dams: a review of research methods', *Environmental Health*, 7(3):84–97.
- Craig IP 2008, 'Loss of storage water through evaporation with particular reference to arid and semi-arid zone pastoralism in Australia', *DKCRC Working Paper 19*, The WaterSmart™ Literature Reviews, Desert Knowledge CRC, Alice Springs.
- Deo AV, Kulkarni SB, Gharpurey MK & Biswas AB 1964, 'Equilibrium film pressure of the monolayers on water of normal long-chain alcohols and normal long-chain alkoxy ethanols', *Journal of Colloid Science*, 19(9):813–819.
- Dressler RG & Guinat E 1973, 'Evaporation control on water reservoirs', *Industrial & Engineering Chemistry Product Research and Development*, 12(1):80–2.
- Drummond CJ, Elliott P, Furlong DN & Barnes GT 1992, 'Water permeation through two-component monolayers of polymerized surfactants and octadecanol', *Journal of Colloid and Interface Science*, 151(1):189–94.
- Federle TW & Itrich NR 2006, 'Fate of free and linear alcohol-ethoxylate-derived fatty alcohols in activated sludge', *Ecotoxicology and Environmental Safety*, 64(1):30–41.
- Fisk PR, Wildey RJ, Girling AE, Sanderson H, Belanger SE, Veenstra G, Nielsen A, Kasai Y, Willing A, Dyer SD & Stanton K 2009, 'Environmental properties of long chain alcohols. Part 1: Physicochemical, environmental fate and acute aquatic toxicity properties', *Ecotoxicology and Environmental Safety*, 72(4):980–995.

- Flexible Solutions 2006, 'Coliban water evaporation reduction trial using WaterSavr'.
<http://www.flexiblesolutions.com/products/watersavr/documents/TheColibanTrial-WaterSavrCaseStudy.pdf>.
- Grundy F 1962, 'Some problems of maintaining a monomolecular film on reservoirs affected by winds', *Retardation Evaporation Monolayers*, papers, symposium, New York, NY, pp. 213–218.
- Gugliotti M, Baptista MS & Politi MJ 2005, 'Reduction of evaporation of natural water samples by monomolecular films', *Journal of the Brazilian Chemical Society*, 16(6A):1186–1190.
- Healy TW & La Mer VK 1964, 'The effect of mechanically produced waves on the properties of unimolecular layers', *Journal of Physical Chemistry*, 68(12):3535–3539.
- Hendel RA, Nomura E, Janout V & Regen SL 1997, 'Assembly and disassembly of Langmuir-Blodgett films on poly[1(trimethylsilyl)-1-propyne]: The uniqueness of calix[6]arene multilayers as permeation-selective membranes', *Journal of the American Chemical Society*, 119(29):6909–6918.
- Herzig MA, Barnes GT & Gentle IR 2011, 'Improved spreading rates for monolayers applied as emulsions to reduce water evaporation', *Journal of Colloid and Interface Science*, 357(1):239–242.
- Jarvis NL 1962, 'The effect of monomolecular films on surface temperature and convective motion at the water/air interface', *Journal of Colloid Science*, 17:512–522.
- Kaganer VM, Mohwald H & Dutta P 1999, 'Structure and phase transitions in Langmuir monolayers', *Reviews of Modern Physics*, 71(3):779–819.
- Kulkarni VS & Katti SS 1982, 'Surface viscosity and pressure-area isotherms of mixed monolayers of hexadecanol with docosanol and hexadecoxyethanol with docosanoxyethanol at 25.0°C', *Journal of Colloid and Interface Science*, 89(1):40–53.
- La Mer VK & Healy TW 1965, 'Evaporation of water. Its retardation by monolayers', *Science*, 148(3666):36–42.
- Langmuir I & Schaefer VJ 1943, 'Rates of evaporation of water through compressed monolayers on water', *Journal of the Franklin Institute*, 235:119–162.
- Larson RJ & Games LM 1981, 'Biodegradation of linear alcohol ethoxylates in natural waters', *Environmental Science & Technology*, 15(12):1488–1493.
- Lonescu M, Mustatea G, Spadaro, G, Vuluga Z & Florea D 2009, 'Characterization of nanocomposite polymer films used for food packaging', *Annals: Food Science and Technology*, 10(2):664–670.
- Machida S, Mineta S, Fujimori A & Nakahara H 2003, 'Retardation of water evaporation by less-defective mixed monolayers spread from bulk solids onto water surface', *Journal of Colloid & Interface Science*, 260(1):135–141.
- McJannet DL, Cook F, Knight J & Burn S 2008, 'Evaporation reduction by monolayers: overview, modelling and effectiveness', *Urban Water Security Research Alliance Technical Report No. 6*.
- McJannet DL, Cook FJ, McGloin RP, McGowan HA and Burn S 2011, 'Estimation of evaporation and sensible heat flux from open water using a large-aperture scintillometer' *Water Resource Research*, 47, W05545, doi:10.1029/2010WR010155.
- Miller IR & Bavly-Luz A 1962, 'Physical properties of monolayers and their relation to evaporation retardation', *Retardation Evaporation Monolayers*, papers, symposium. New York, NY, pp. 161–175.

- Morrison P, Gill R, Symes T, Misra R, Craig I, Schmidt E & Hancock N 2008, 'Small scale evaporation mitigation trials, 2007–08', *National Centre for Engineering in Agriculture, Publication 1002040/1*, Toowoomba, Queensland, Australia.
- National Water Commission 2008–11, *Australian water markets reports*, NWC, Canberra.
- Prime EL, Tran DNH, Leung AHM, Sunartio D, Lim J, Qiao GG & Solomon DH 2012, 'Formation of new monolayer systems at the air/water interface by using non-ionic hydrophilic polymers', submitted.
- Reiser CO 1969, 'System for controlling water evaporation', *Industrial & Engineering Chemistry Process Design and Development*, 8(1):63–9.
- Rideal EK 1925, 'Influence of thin surface films on the evaporation of water', *Journal of Physical Chemistry*, 29:1585–8.
- Saylor JR, Smith GB & Flack KA 2000, 'The effect of a surfactant monolayer on the temperature field of a water surface undergoing evaporation', *International Journal of Heat and Mass Transfer*, 43(17):3073–3086.
- Solomon DH, Prime EL, Sunartio D, Qiao GG, Blencowe A & Dagley I 2010, 'Method for controlling water evaporation', *PCT International Application*, WO 2010071931.
- Steber J & Wierich P 1985, 'Metabolites and biodegradation pathways of fatty alcohol ethoxylates in microbial biocenoses of sewage treatment plants', *Applied and Environmental Microbiology*, 49(3):530–537.
- UNEP (United Nations Environment Programme) 1995, '1-octadecanol, CAS 112-92-5' *OECD SIDS report*.
- Vendra VK, Wu L & Krishnan S 2007, 'Polymer thin films for biomedical applications', in *Nanotechnologies for the Life Sciences*, Wiley-VCH Verlag GmbH & Co. KGaA.
- Winter M & Albrecht B 2011, 'Predicting the optimum time to apply monolayers to irrigation channels', *NPSI Report*, NPSI2611.
- Yao X, Zhang H, Lemckert C, Brook A & Schouten P 2010, 'Evaporation reduction by suspended and floating covers: overview, modelling and efficiency', *Urban Water Security Research Alliance Technical Report No. 28*.

12.1 Further information

Several resources and case studies related to managing evaporation on farm water storages can be found on the National Program for Sustainable Irrigation website (www.npsi.gov.au — search for 'evaporation').