



THE BENEFITS OF SHADE-CLOTH COVERS FOR POTABLE WATER STORAGE

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CSIRO TEXTILE & FIBRE TECHNOLOGY



Glossary

ML	Megalitre = 1×10^6 L or 1000 kL or 1000 m ³
RH	Relative Humidity (moisture content relative to moisture content at saturation at current air temperature, expressed as percentage)
T	Temperature [°C]
Chlorophyll	In this context refers to total chlorophyll as measured by the submerged fluorescence measurement device in µg/L, indicator of all photosynthesising algae.
E	Evaporation Rate: rate of loss of water through evaporation, expressed in mm/day
N	Total Nitrogen [mg/L]
P	Total Phosphorous [mg/L]
mg/L	milligram per Litre 1×10^{-3} g / L
Coliforms	Bacteria of the coliform group, indicator of water quality [organisms/100 mL].
E. Coli	<i>Escherichia coli</i> bacteria, common bacteria used as indicator of faecal contamination of water and is a potential cause of illness. [organisms/100 mL].
Colilert	Water samples tested in a NATA approved water quality testing laboratory
In-House	Water samples tested at East Gippsland Water internal testing laboratories
U _o	Wind speed [ms ⁻¹] at surface (water or land)
U(h)	Wind speed [ms ⁻¹] at height, h [m]
z	Roughness scale length of land or water surface (m)
V _p	Moisture Vapour pressure [mbar]
V _{sat}	Saturation moisture vapour pressure [mbar] at current air temperature
Minisonde	Hach Hydrolab Minisonde 4A submerged sensor system incorporating depth, T, pH, specific conductivity, salinity, turbidity, with separate but bundled Turner Designs Chlorophyll fluorometer “SCUFA” Self Contained Underwater Fluorescence Apparatus.
Datasonde	Hach Hydrolab Datasonde 4a submerged sensor system incorporating depth, T, pH, specific conductivity, salinity, turbidity (with wiper), integrated Turner Designs Cyclops-7 submersible fluorometer.



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Executive Summary

The use of shade-cloth covers for water storages has several aims:

- To improve water quality by:
 - Reducing light levels to prevent algal and plant growth
 - Reducing wind-borne contaminants
 - Preventing access to birds
- Reduction of evaporation
- Improved security of supply
- Reduced chemical usage
- Improved security against wilful contamination

The project ran over two years from 2004 to 2006 with four basins monitored for one year uncovered and one year covered. Two of the basins were treated-water storages (Mallacoota and Omeo) and two were raw-water storages (Swifts Creek and Cann River). Two control basins (Sarsfield & Orbost) were monitored for two years uncovered, these were respectively raw-water and clear-water basins. Analysis of the enormous data set generated has shown that the incidence of algal blooms was dramatically reduced by the presence of the covers. In the case of the Omeo clear-water basin the cover has prevented algal growth to such a degree that the basin can be used reliably as weekend supply in summer for the first time ever; this has reduced labour costs significantly. Water fowl can no longer access the basins but small birds and animals can still enter through small holes. Wind-borne organic materials are less likely to enter the water storages. The skirting systems initially installed were inadequate and allowed the wind to carry debris into the basins but this has since been remedied by better skirt design. Plants no longer grow at the bottom of the basins because of the lack of light and this will reduce maintenance costs. In the case of raw-water storages the frequency of adverse bacterial events has not been as greatly reduced as for treated water storages. This is because raw-water storage bacterial/algal contamination is usually the result of pumping from bacteria/algae laden rivers. In the case of treated-water storages the incidence of adverse bacterial events (total coliforms and *E.coli*) was greatly reduced. Minor chlorophyll

events also occurred at raw water storages after covering, these were due to pumping contaminated water from the primary source but the algae quickly died out, more quickly than when uncovered due to the lack of light and despite high nutrient levels. These high nutrients again originate from the primary water source. Since covering no remedial action with respect to algae or bacteria, such as algacide dosing or draining of the basin, has been required. A dramatic increase in total chlorophyll and bacteria at Omeo clear water storage and Swifts Creek raw water storage in February 2006 was found to be caused by a plague of locusts, which is an extremely rare event. Locusts died in the water releasing their stomach contents, which contained plant material. The same effect was observed for a few locusts in a beaker in the site laboratory.

The optical instruments sometimes suffered from direct contamination by algae; contamination cannot easily be avoided but their design could perhaps be improved to reduce it and to render their measurements more immune to it. The fluorometer contamination reduced confidence only in the absolute chlorophyll values but these were not relied upon to determine changes in algal abundance as manual samples were also taken throughout the study and laboratory counted. The *in-situ* instruments did provide continuous chlorophyll data with fine time and depth resolution and the temperature and other measures provided by the instrument were also invaluable. Examples of the algal abundance in covered and uncovered basins are shown below, for Mallacoota and Sarsfield. (Figures 1 & 2)

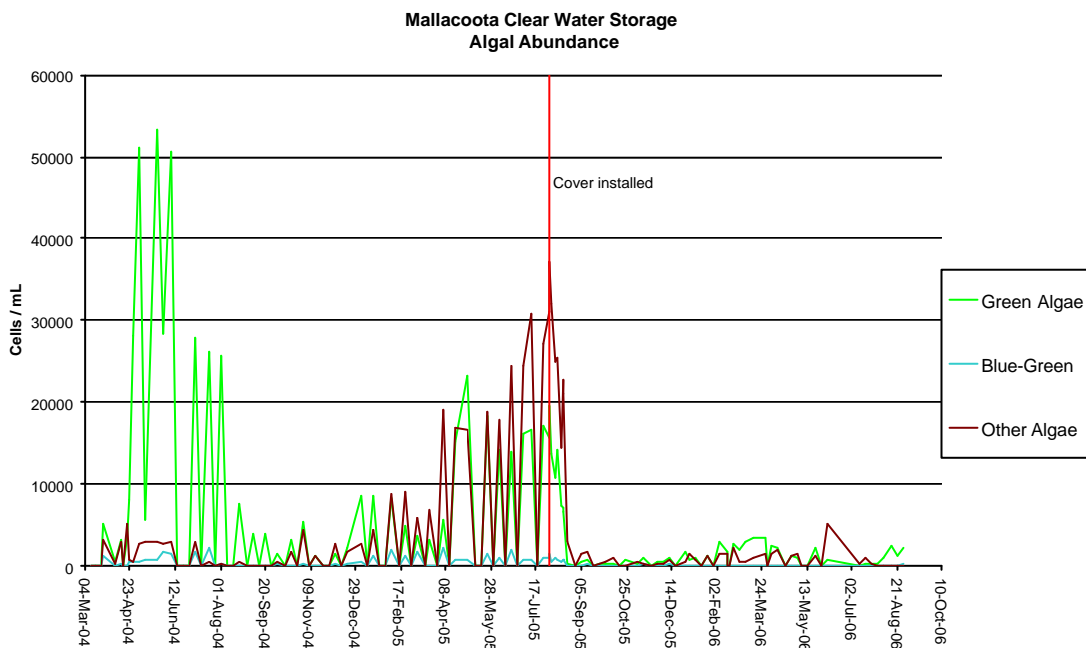


Figure 1. Mallacoota algal abundance showing large decrease in activity after covering.

Sarsfield Raw Water Storage (Control)

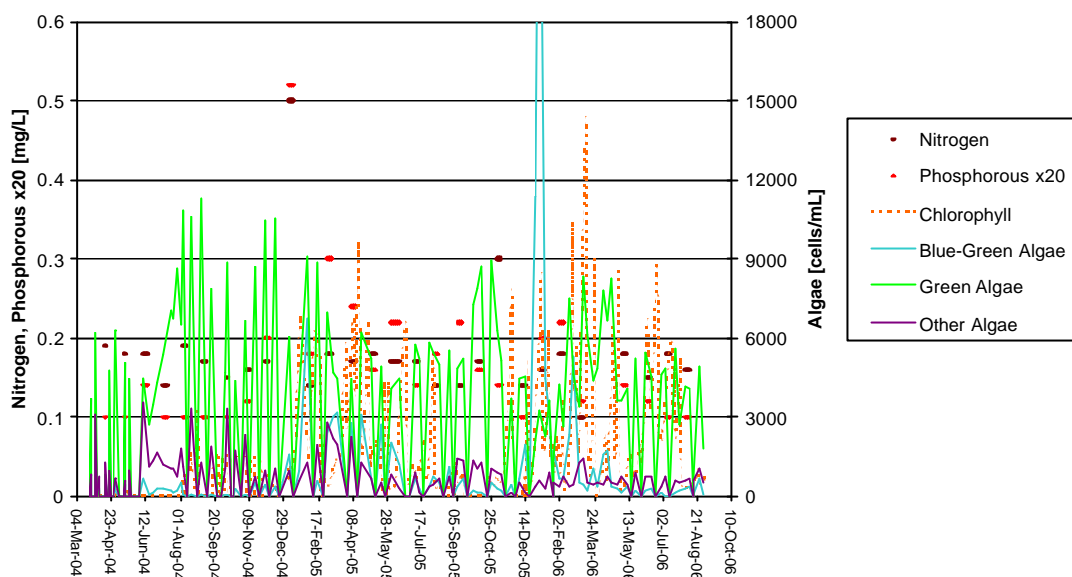


Figure 2. Sarsfield Basin was not covered for the whole period of the study and shows high algal activity in both the period before the other basins were covered and afterwards indicating that the changes that occurred with covering were not due to seasonal variations.

The algal blooms were often accompanied by strong diurnal oscillations in pH, due to oscillations between respiration producing CO₂ and photosynthesis consuming it during daylight hours. A preliminary study of these results suggests that diurnal oscillations in pH could possibly be used as a low cost monitor for algal activity in water storages.

Evaporation rates appear to be dramatically reduced. Pan evaporation was measured at each site remote from the basin but next to the land weather station, while evaporation from the basin was calculated using the data measured by the floating weather station on the water (Figure 3). The model used to calculate basin evaporation is a well established bulk aerodynamic method [1] that uses air temperature and humidity, water surface temperature and wind speed to calculate the evaporation rate. A fitting parameter was adjusted using the measured annual pan evaporation rate for the site and then this parameter used in the calculation of basin evaporation rate using the weather and water temperature data obtained on the water. Annual evaporation rate estimates ranged from 870 mm to 1060 mm per year across the sites (see Table 1). At Mallacoota (Figure 4), the largest covered basin, the estimated evaporative loss is equivalent to 8.5 ML of water per annum. Directly measured pan evaporation rates ranged from 660 mm to 1025 mm across the sites. A definitive measurement of pre-cover versus post-cover losses was not possible. Omeo was expected to be the ideal site where the evaporation model could be validated as it was a fully lined basin and so seepage was expected to be zero. However, a problem with the inflow meter meant that an accurate water balance wasn't possible. At all other sites losses are a combination of seepage, evaporation and operational losses and the losses are a small fraction of the total flows and so very accurate measurement of flows over long periods of time are required. The air speed under the covers is effectively

zero when the skirts are properly fitted and so normal turbulent surface evaporation is prevented. However, it might have been expected that moisture could diffuse up to and through the shade cloth and be removed by air currents over the outside surface, however this was shown to be only about 10% of normal evaporation from a free water surface. Individual relative humidity (RH) and temperature monitors were suspended at various heights at Cann River after it was covered to determine the temperature and RH profile in the air column between the cover and the water surface and above the cover. These results when combined with laboratory measurements of fabric permeability suggest that the evaporation rate of a covered basin is less than 10% of that for the basin uncovered, i.e. approximately 90% reduction in evaporation rate. This is due to the zero wind speed, stable air temperature profile, lower water surface temperature under the cover, the finite cover permeability, and reduced vapour pressure difference at the interface. In the uncovered case the interface is the open water surface where the vapour pressure is at saturation. When the basin is covered the interface is at the fabric surface and the internal vapour pressure is much closer to the external vapour pressure and diffusion is reduced by the fabric.



Figure 3. *Floating Weather Station*

Table 1. Evaporation Summary. Evaporation rate estimates without covers.

Site	Daily Evaporation (mm/day)		Annual Evaporation (mm/yr)		Water type	Capacity (ML)	W x L x D (m)	Loss ML/yr
	Basin	Pan	Basin	Pan				
Omeo	2.4	1.8	870	660	Clear	5.2	30x50x3	1.3
Cann River	2.9	2.5	1060	895	Raw	3	30x30x2.3	0.95
Mallacoota	2.8	2.0	1016	725	Clear	22.8	90x110x4.6	10.1
Sarsfield	2.9	2.2	1060	810	Clear	160	80x80x6	6.8
Orbost	2.4	2.1	876	760	Raw	53	55x150x5	7.3
Swifts Creek	2.9	2.8	1060	1025	Raw	4	40x60x3	2.5

Some practical design issues remain to be addressed with the covers themselves, including abrasion/puncture against rock-beaching, structures under the covers, and problems with the entrances and skirts. These will be completed by the structural engineers and improvements incorporated into future designs. Temperature stratification of the water column was shown to occur at various times in both covered and uncovered basins during hot weather. The temperature gradients appear to be more persistent but smaller in magnitude in covered basins due to reduced evaporation and hence reduced evaporative cooling and to the insulating effect of the covers. If stratification causes quality problems, for covered or uncovered basins, mixing can be achieved by several simple means. During this study mixing and aeration was occasionally required to oxidise high metal levels and this was achieved by using submerged perforated plastic piping and a high pressure air blower.



Figure 4. Mallacoota Clear Water Storage with cover

The improved water quality and massively reduced risk of algal blooms and other contamination provided by the covers offers a valuable enhancement in security of water supply. Maintenance costs with respect to aquatic plant growth would also be expected to be reduced. Evaporation reduction, while not the primary motivation for covering basins, is highly significant and in circumstances where alternative water supplies are not available potentially valuable.

Introduction

The study was conducted in East Gippsland, Victoria, in collaboration with East Gippsland Water, Gale Pacific who manufactured the shadecloth, and SuperSpan who designed and installed the covers. At each site there is installed:

- Water Weather Station
- Land Weather Station
- Evaporation Pan
- Solar monitor
- In-Flow monitor
- Out-Flow monitor
- Minisonde-SCUFA monitoring:
 - Algae (Chlorophyll A by fluorometer)
 - pH
 - Temperature
 - Salinity
 - Specific conductivity
 - Turbidity
 - Depth

Each of the water storage basins is different in its layout, operation and the characteristics of its water source, and each had particular challenges in installation and set up of the instrumentation. All the basins were being monitored from April 2004. Four of the six basins were covered in 2005 with varying delays to cover installation. Two basins remained uncovered for the whole study to act as controls. The basin locations are shown on the map below (Figure 5) and the basin parameters are in Table 2.



Figure 5. Map of Victoria showing water storage sites.

Table 2. Basin properties at each site.

Site	Water type	Capacity (ML)	W x L x D (m)
Cann River	Raw	3	30x30x2.3
Swifts Cr	Raw	4	40x60x3
Omeo	Clear	5.2	30x50x3
Mallacoota	Clear	22.8	90x110x4.6
Sarsfield	Raw	160	80x80x6
Orbost	Clear	53	55x150x5

Installation of the main instruments was completed at five of the six sites before the end of March 2004. At the sixth site, Sarsfield, the Minisonde-Scufa water quality probe was not operational until April 20th as it failed and needed to return to the USA manufacturer for repair under warranty. The Minisondes had to be returned to the US manufacturer for repair on numerous occasions but four have been replaced with newer Datasonde devices, which have proved more reliable. The Datasondes and Minisondes are particularly useful in measuring variations on a short time-scale and variations with depth. At each site the “Scufa” (Minisonde or Datasonde devices) are mounted within a 30 cm polystyrene float connected by a stainless steel cable via a pulley at the bottom of each basin to a winch on the bank whose operation allows the instrument to be scanned slowly through the depth of the water, once every two hours (Figure 6).



Figure 6. Datasonde depth scanning mechanism.

This provides a profile for each of the water quality measures with depth. As algae (especially potentially toxic blue-green algae) are known to adjust their depth to the most favourable conditions it allows their detection even if they are occupying only a thin layer. It is also considered possible that when covered some basins would be more prone to stratification and the depth scans allowed temperature profiles to be measured.

The fluorometers give interesting data on the growth rates of algal blooms but their interpretation must be qualified by the problem that the algae often grew directly on the devices causing them to give a spuriously higher signal than would have been obtained from a clean device. It was not practical to clean the devices with sufficient regularity to

measure growth rates with absolute certainty. However, the algal abundance, bacterial counts, and chemical composition tests were performed at least every three weeks by manual sampling and so the fluorometer data was not relied upon to measure changes in these parameters. The Datasonde temperature and pH measurements were also very useful. It was observed that when algae were present in large numbers the pH oscillated with daylight as algae produce CO₂ with respiration (day and night) but consume CO₂ during the day via photosynthesis. The diurnal pH oscillations remained at similar levels for clean and dirty instruments while the total chlorophyll signal often dropped significantly when the algae was cleaned from it.

The temperature measured at the surface is used in combination with the air temperature, RH and wind speed to calculate an estimate of the evaporation rate by the bulk aerodynamic method. In addition, the inflow and outflow and depth measures were intended to provide total losses, including seepage, and with the evaporation pans allow a check of the evaporation model. The basin at Omeo is lined with an impervious material and so evaporation is the only loss expected. This was to be the “model” basin to check the aerodynamic evaporation model; however, it was discovered too late that the in-flow meter was inaccurate due to sucking air into the pipe. A parameter of the aerodynamic model was adjusted to model the measured evaporation pan losses and then the same parameter used to model basin losses using basin weather data and after adjusting for the different measurement height and surface roughness. Once basins are covered and skirts attached the airflow inside is negligible, and so evaporation is severely reduced. However, the air under the cover becomes very humid and there is a possibility for water vapour to be transported through the permeable cover, especially when a drier air flow is passing over it. Various measurements have been taken of the air column under and above the covers and these suggest that evaporation from a covered basin was less than 10% of that of an uncovered basin.

Monitoring of chlorine usage at all sites except Sarsfield required additional hardware or modifications to pumps and was not fully implemented. Sarsfield uses gaseous chlorine in a continuous flow system and a signal was available for monitoring the gas flow rate. Manual records of chemical usage were to be obtained but due to staff turnover this was not reliable. Therefore the only chemical usage data reported was from Sarsfield.

The data sets allow detailed inspection of events at each of the basins, but due to the sheer quantity of data only summaries for each basin are reported here along with some examples of the details of some interesting events.

ALGAE and BACTERIA

MALLACOOTA Clear Water Storage

The Murrumbidgee water supply is sourced from the Betka River. The water undergoes full water treatment (Coagulation / Flocculation / Sedimentation and Filtration) and is transferred into a Clear Water Tank. During times of low demand the Clear Water Tank overflows into a 22.8 ML Clear Water Storage Basin. The storage basin is a clay-lined, rock beached turkey nest design. During times of high demand, the Clear Water Tank supply was augmented with water from the Clear Water Storage. This water was not retreated through the treatment plant but transferred into the reticulation mains after being re-chlorinated. Historically the Clear Water Storage experienced high algal numbers during Summer / Autumn. This resulted in 'tainted' water being delivered to customers with incidences of turbidity, taste and odour being recorded. This effectively negated the benefits gained via full water treatment.

Figures 7 – 9 below show the impact of covering the basin – reduced numbers of algal species and abundance as well as reduced bacterial levels indicating that reduced recontamination of the water after treatment has been achieved.

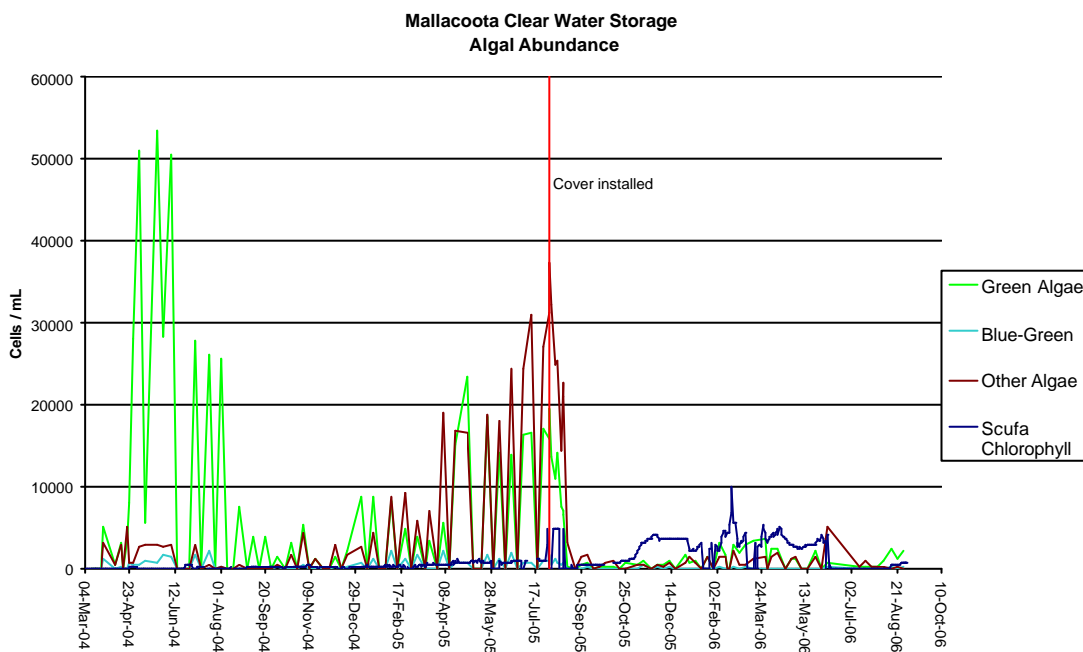


Figure 7. Mallacoota algal abundance, shows a dramatic reduction in algal blooms after covering.

After the cover was installed the basin suffered several extremely high turbidity events. The cause of these was thought to be as a result of accumulation of sediment and flocculant carryover from the treatment plant over a number of years and subsequent disturbance of this accumulated debris during capital works modifications of the bore water inlet to the storage basin. Eventually the basin was drained and large quantities of sludge pumped out. Since this operation the basin has been extremely reliable.

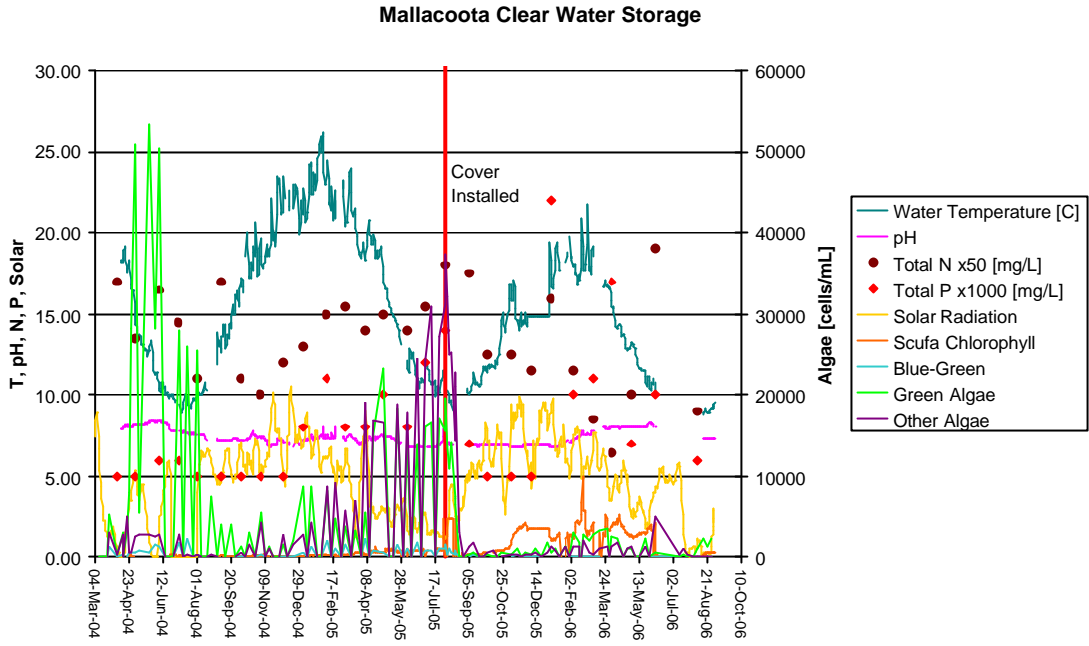


Figure 8. Mallacoota algal abundance with water temperature, pH, nutrient levels and solar radiation. Note that algal blooms can occur in winter when light levels and water temperatures are lower. This graph also shows that nutrient levels are not limiting growth since they are just as high after covering as before.

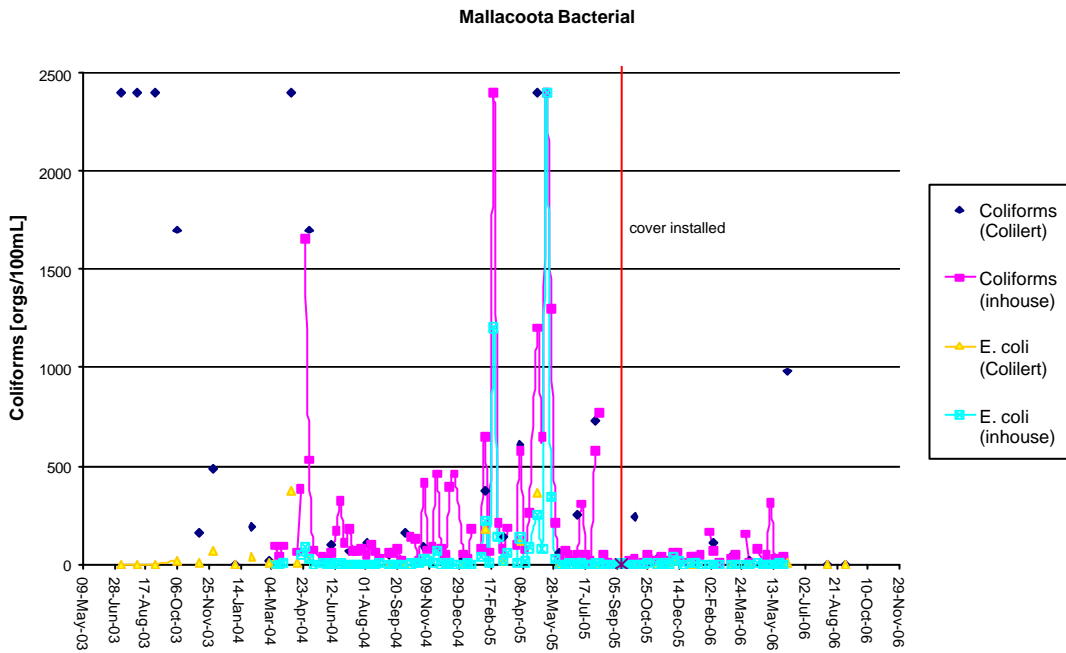


Figure 9. Mallacoota bacterial test results. Covering has reduced the frequency of bacterial contamination; probably due to the exclusion of water birds.

OMEEO

The township of Omeo is supplied by fully treated water from Butchers Creek. A similar system to that outlined for Mallacoota is operated in Omeo – full water treatment into a Clear Water Tank which overflows into a Clear Water Storage during periods of low demand. Unlike Mallacoota, this 5.2 ML storage is fully lined with a water tight liner. As with Mallacoota, the recontaminated treated water (either by algal growth, bacterial contamination via water birds roosting or windblown debris) resulted in poorer quality water being delivered to consumers during periods of high demand when the Clear Water Storage supplemented / replaced the Clear Water Tank supply.

In previous summers algal blooms rendered the Omeo Clear Water Storage unusable for significant periods of time. Covering the basin has allowed it to be used throughout the last summer, especially over weekends, significantly reducing the labour required to tend the treatment plant during these periods.

Since being covered, and apart from the locust infestation, the Omeo storage has not suffered any algal or bacterial contamination that has required remediation such as algicide dosing or drainage and cleaning. The operations of the overall WTP have been enhanced due to the increased reliability of the storage (Figures 10-12).

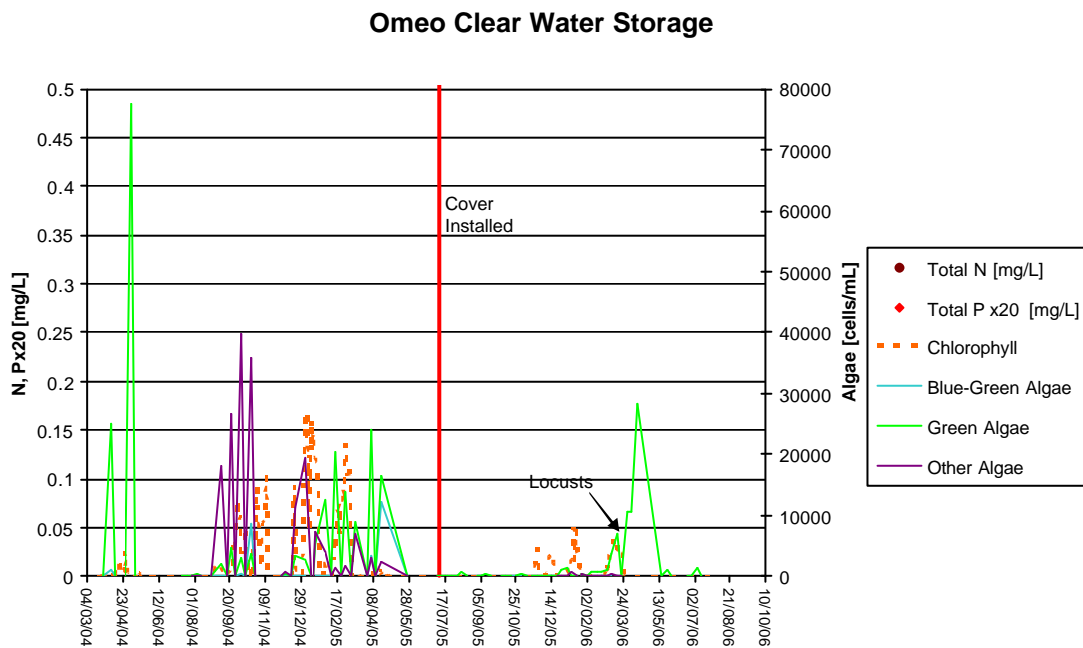


Figure 10. Omeo clear water storage algal abundance. High nutrient levels accompany periods of high algal growth. The short spike in green algae in April 2006 is anomalous and did not require any action.

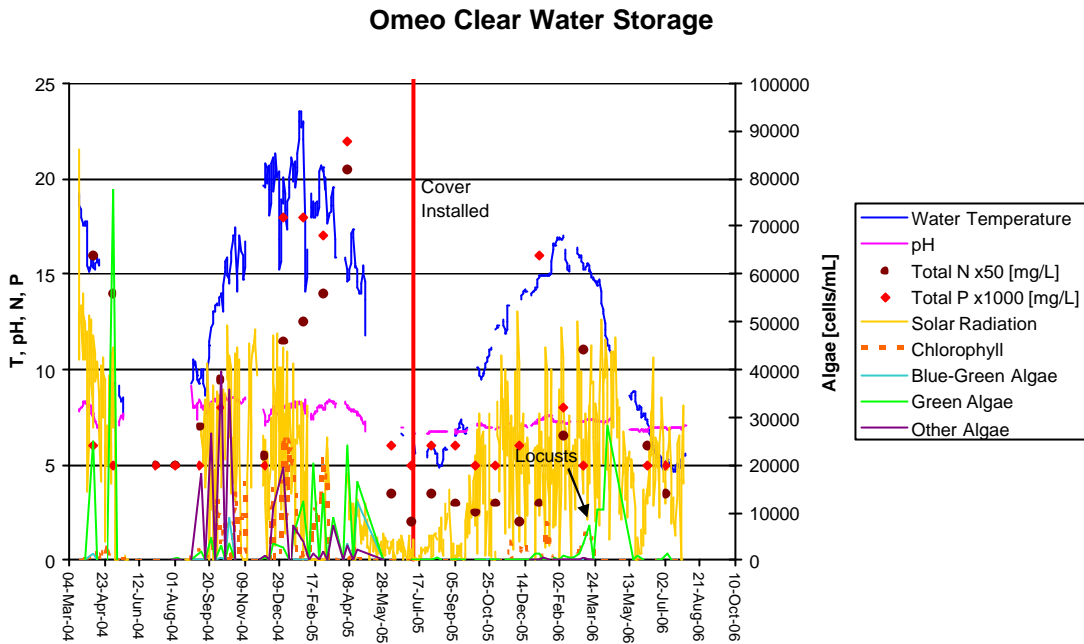


Figure 11. Omeo algal abundance with water temperature, pH, nutrients and light levels. The water is cooler and less variable after the basin is covered despite very high air temperatures inside the cover.

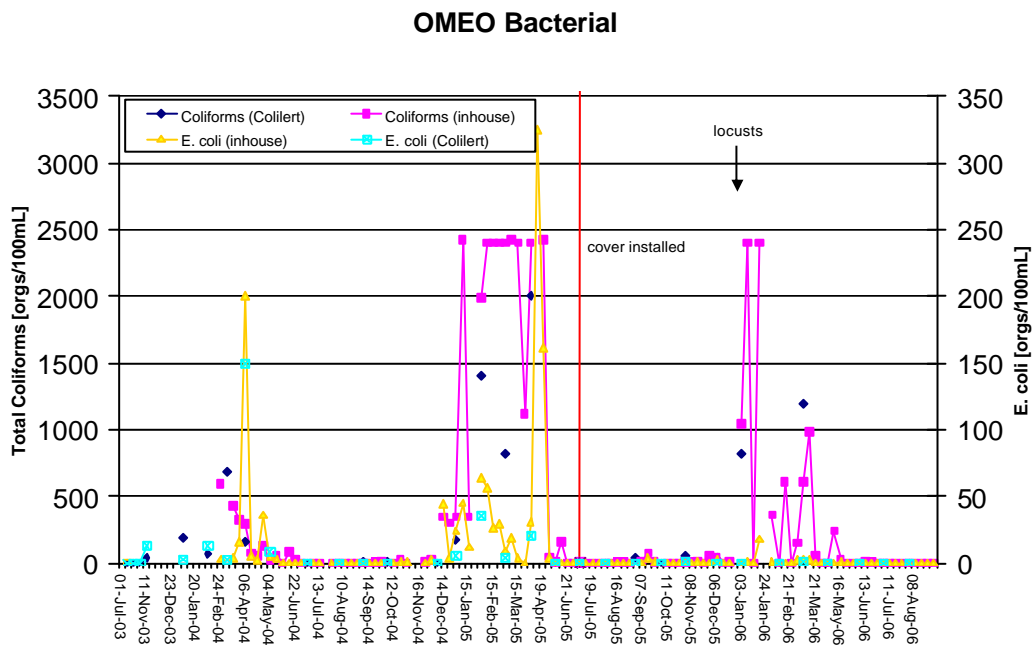


Figure 12. Omeo clear-water storage bacterial contamination. Note that the event in February-March 2006 was a locust infestation.

Cann River

The township of Cann River is supplied by water harvested from Cann River into a Raw Water Storage Basin, disinfected with sodium hypochlorite at the outlet of the basin and fed directly into the reticulation system. There is no further treatment of this water. Historically the water quality was affected by coloured water / high iron content water harvested from Cann River as well as algal growth in the Raw Water Storage. As can be seen from Figures 13 – 15 below, there was significant impact on algal abundance and occurrence in the storage after covering. There was a lesser impact on bacterial levels due to ‘re-seeding’ of the storage with bacteria from the river with every pumping event. Disinfection of the water at the outlet of the storage addressed the bacterial hazard; however, this process sometimes exacerbated taste and odour issues originating from the presence of algae.

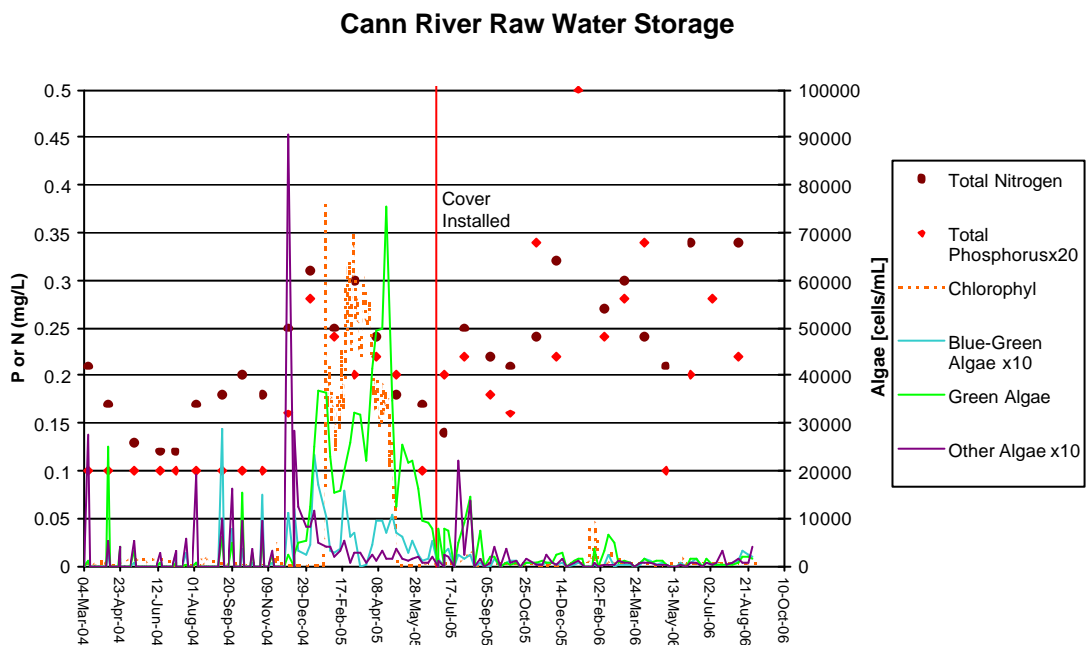


Figure 13. Cann River raw water storage algal abundance. Despite high nutrient levels since covering there have been no significant blooms.

Cann River Raw Water Storage

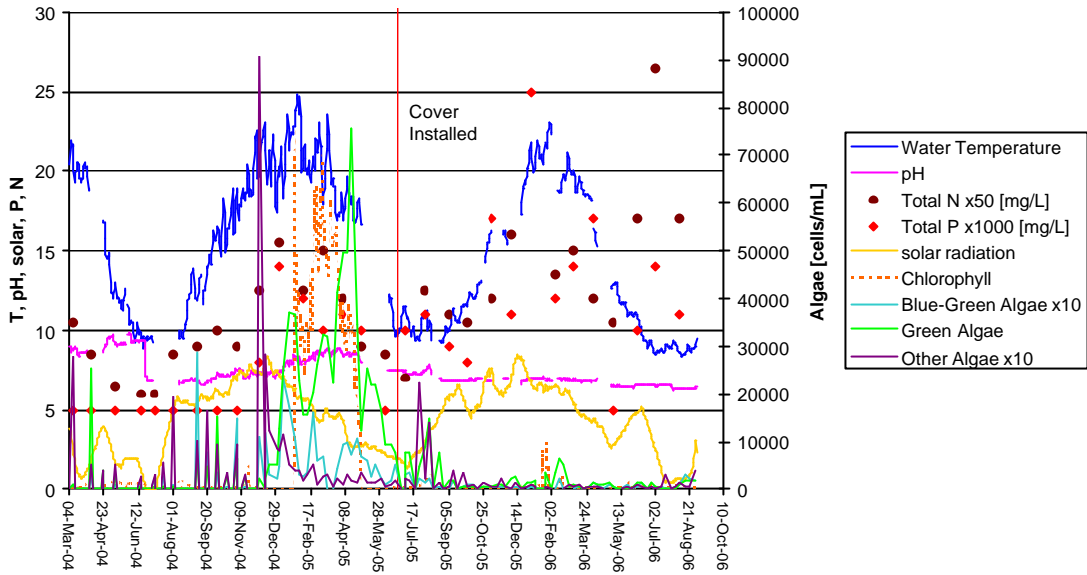


Figure 14. Cann River raw water storage algal abundance with water temperature, pH, nutrients and solar radiation. Despite warm weather and high nutrient levels no algal blooms occurred.

Cann River Bacterial

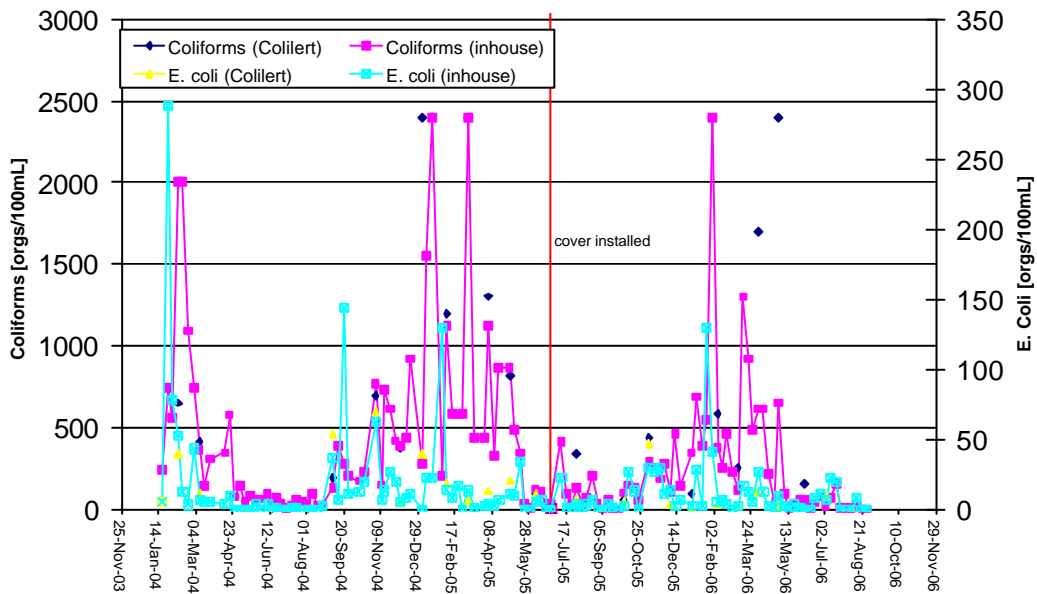


Figure 15. Cann River bacterial contamination. The cover has made little difference to the bacterial levels because this is a raw water storage and if the water source is contaminated then so will be the storage.

Swifts Creek

The township of Swifts Creek is supplied by water harvested from the Tambo River, stored in a rock lined / beached 4 ML Raw Water Storage and disinfected with chlorine dioxide at the outlet of the storage. There is no further treatment of the water prior to delivery to consumers. In the past the water supply has experienced a number of taste and odour problems due to the presence of algae and aquatic plants – predominantly *Chara* sp. which imparts an “off fish” taste and odour to the water. As with Cann River, covering of the storage had a significant impact on algal occurrence and abundance but less impact on bacterial levels (Figures 17-19). Prior to covering the Swifts Creek Raw Water Storage, it was drained and most of the aquatic plants were removed.



Figure 16. *Swifts Creek basin being cleared of aquatic plants*

Clearing of aquatic plants from water storages, as shown in Figure 16 above, is an expensive and inconvenient operation and the basin is off-line for several days.

Video records and visual monitoring of the storage after the cover was installed showed a dramatic decrease in the regrowth of the aquatic plants with no plants reappearing in the middle of the storage where light levels were lowest and with minimal regrowth occurring where sunlight came through ‘gaps’ in the cover, at the bases of support poles and around the inlet structure.

Swifts Creek Raw Water Storage

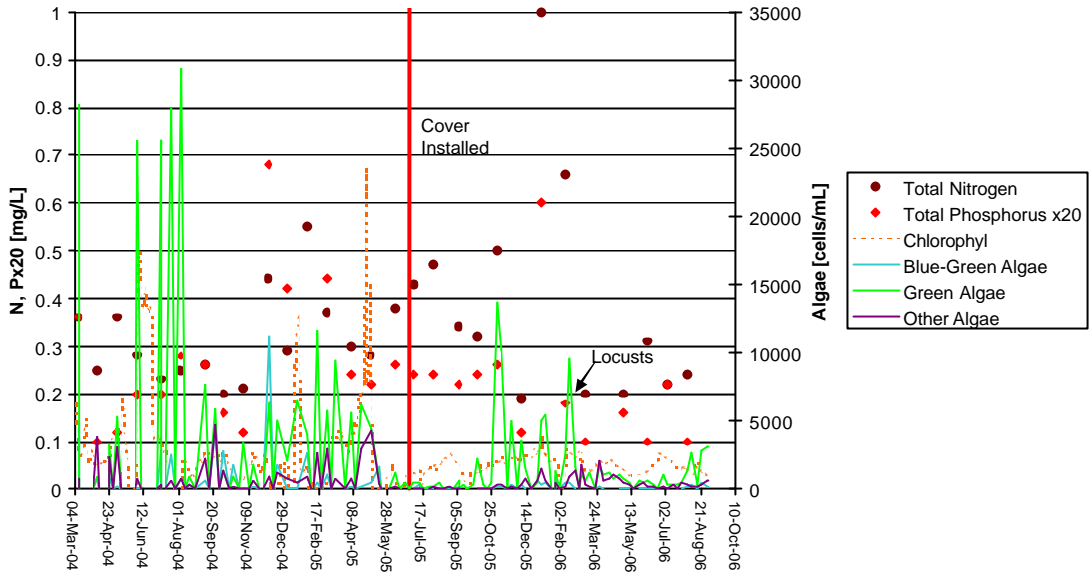


Figure 17. Swifts Creek raw water storage algal abundance. Note the presence of locusts ; Swifts Creek is only 20 km from Omeo and was impacted at the same time .

Swifts Creek Raw Water Storage

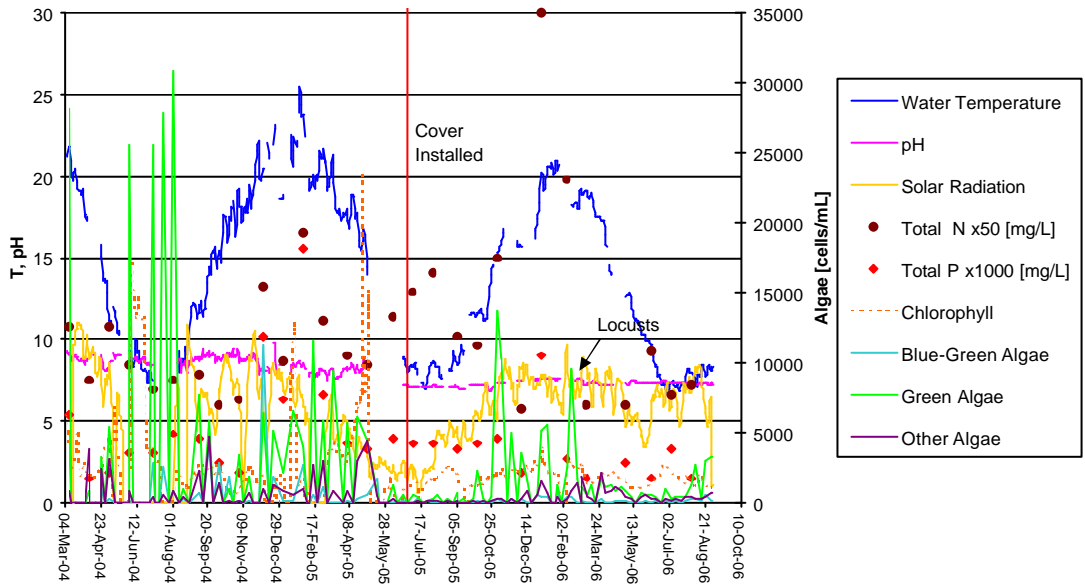


Figure 18. Swifts Creek algal abundance with water temperature, pH, and nutrients

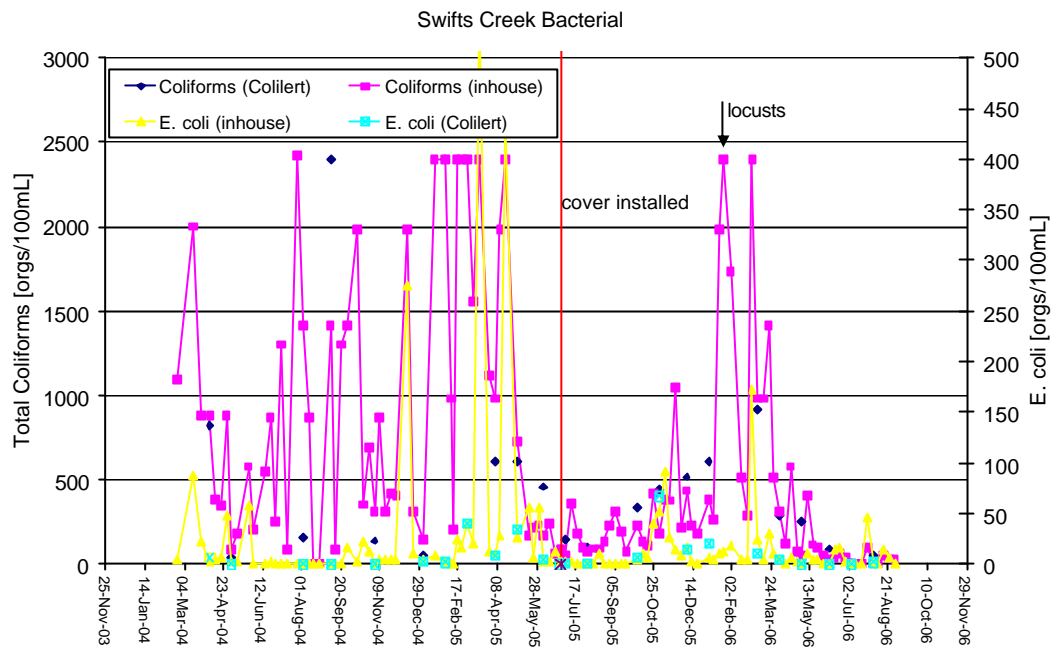


Figure 19. Bacterial levels at Swifts Creek were reduced by the cover but because it is a raw-water storage and the river is a source of contamination, significant levels still occurred after covering. The highest levels in the post-cover period coincided with the dead locusts.

Sarsfield

Sarsfield Storage Basin is a 160 ML earthen, rock beached storage. Water harvested from the Mitchell River at Glenaladale is transferred to this storage and used to supply the townships of Sarsfield, Bruthen, Nicholson, Johnsonville, Swan Reach, Metung and Lakes Entrance. The water is disinfected using chlorine gas at the outlet of the storage.

Sarsfield was one of two basins that were monitored without covering for the two year period. While not strictly an experimental control because the size, location, and operations were not identical the uncovered basins, one Raw Water and one Clear Water basin provided a degree of confidence that seasonal variations could be accounted for. Thus a change in the second year after covering at one of the covered basins could be checked against an uncovered basin in the same year. Sarsfield is the largest of the basins studied with a depth of 6.5 m.

Sarsfield Raw Water Storage (Control)

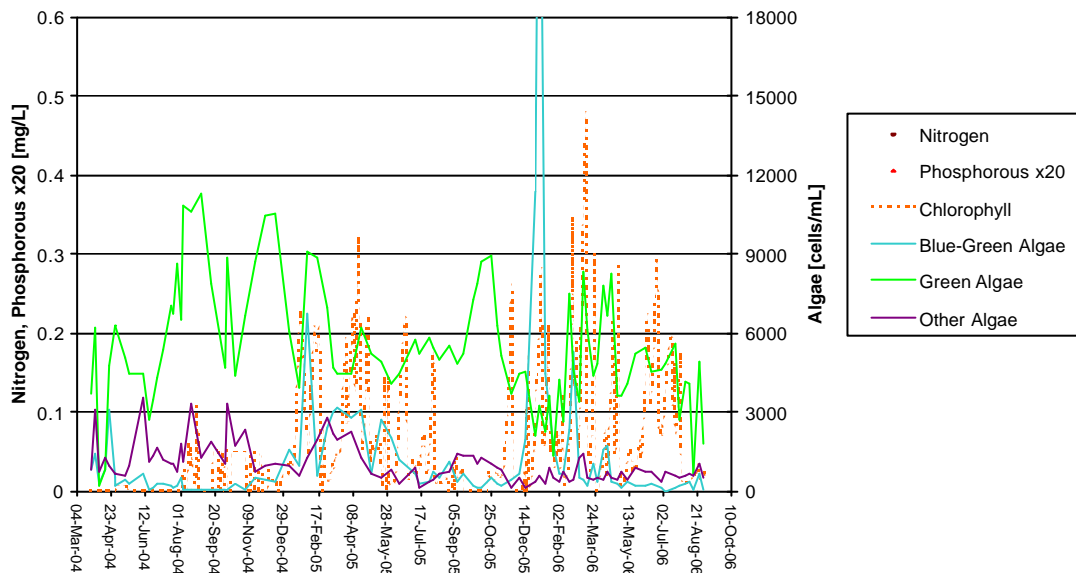


Figure 20. Sarsfield algal abundance.

Sarsfield Raw Water Storage

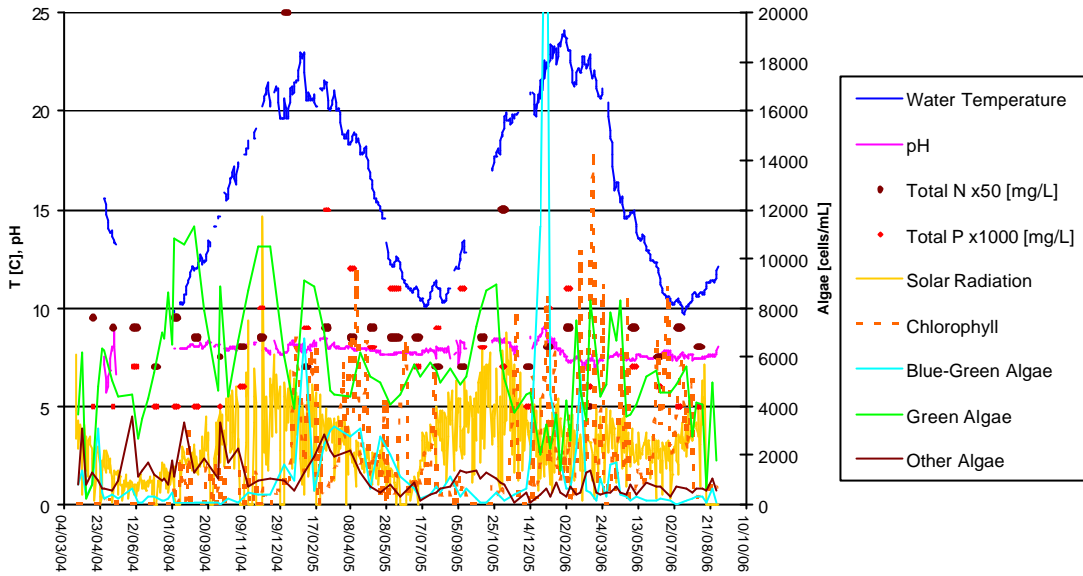


Figure 21. Sarsfield algae plotted with water temperature, pH, solar radiation, and nutrient levels.

Figure 21 shows algal abundance plotted with water temperature, pH, solar radiation, and nutrient levels. This shows some influence of nutrients and light levels on the growth of green algae in particular. The large but short lived bloom of blue-green algae in February 2006 appeared to occur when neither nutrient levels nor light levels were especially high.

Sarsfield Bacterial

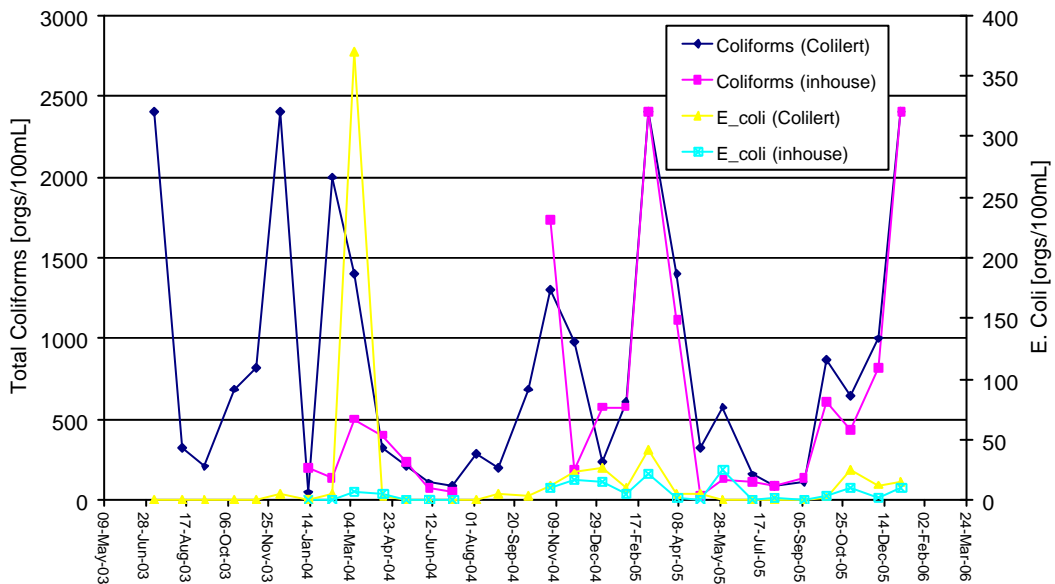


Figure 22. Sarsfield Bacteria results.

Figure 22 shows the results of bacterial testing at Sarsfield. There is little difference between the two years of the study. There was only one incidence of significant *E.coli* presence, in March 2004, and several occurrences of significant total coliforms present.

Chlorine Usage

Figure 23 shows the rate of chlorine use. Gaseous chlorine is used as a disinfectant. The chlorine used per hour is plotted against the total algae test results. The chlorine injection is flow paced but is also mediated by the residual chlorine in the treated water so if there is more organic material present then more chlorine is required to maintain the residual level. It can be seen that the chlorine usage rate is somewhat linked to the algal abundance, suggesting that reduced algae would be expected to reduce the chlorine usage.

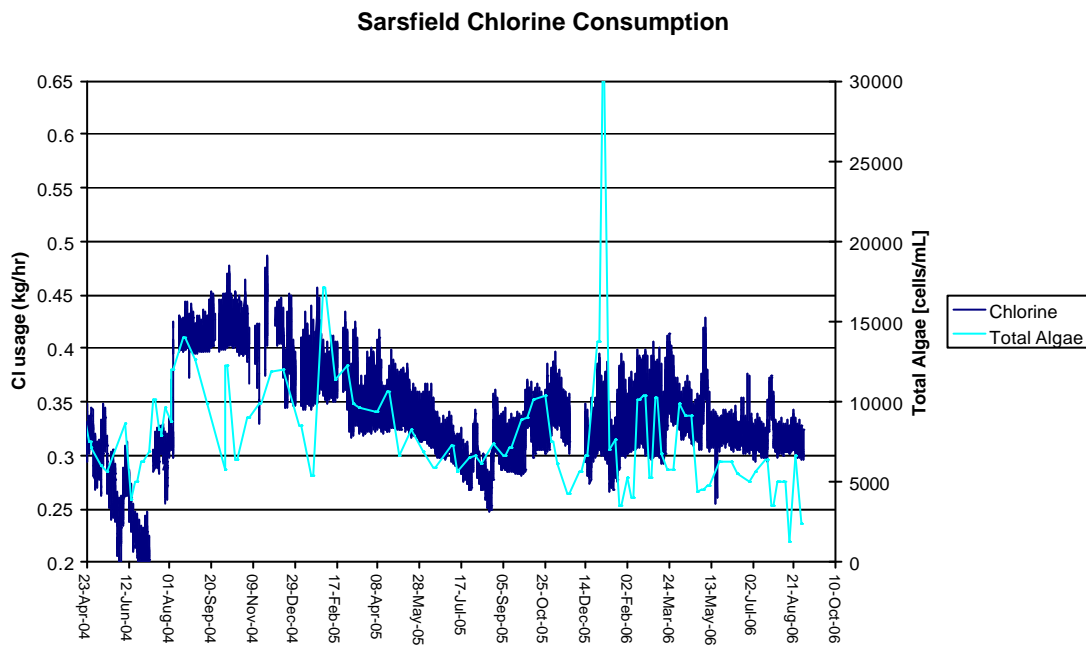


Figure 23. Chlorine usage at Sarsfield.

Orbost

The township of Orbost is supplied with water harvested from the Brodribb River and Rocky River. This water is stored in a Raw Water Storage and undergoes full water treatment (coagulation / flocculation / sedimentation / filtration). The treated water is transferred to a Clear Water Tank which is chlorinated at the outlet prior to entry into the reticulation system. Overflow from the Clear Water Tank is stored in a 53 ML earthen, rock beached Clear Water Storage. During periods of high demand, this water is re-chlorinated prior to boosting supply into town. Orbost is the second “control” site; it was uncovered for the whole study (Figure 24-26).

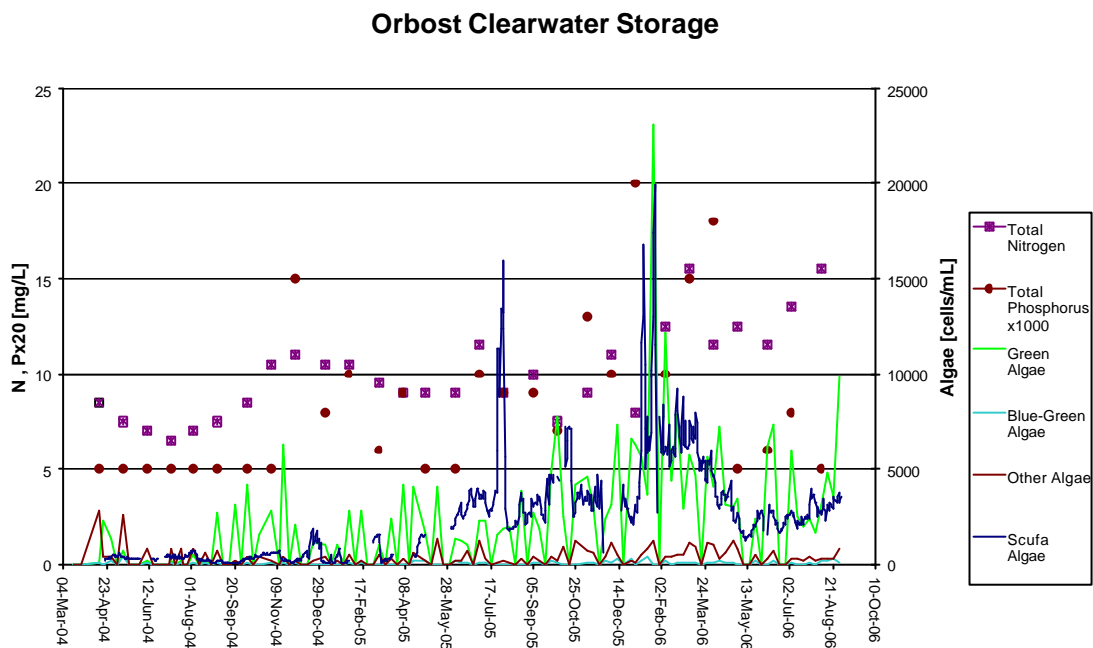


Figure 24. Orbost Algal abundance.

Orbost Clear Water Storage

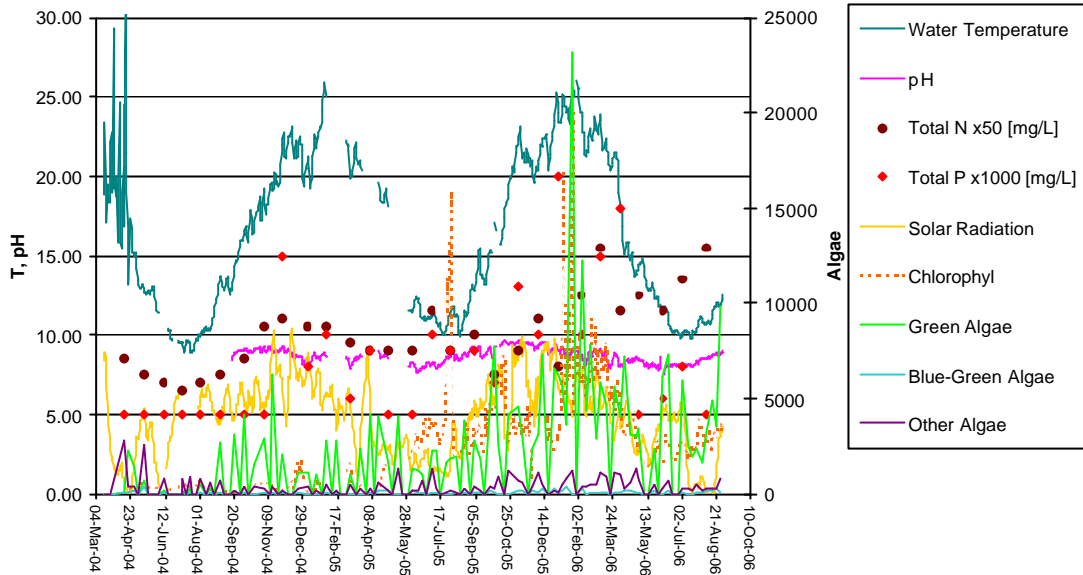


Figure 25. Orbost Algal abundance, water temperature, and pH.

Orbost was relatively free of algal blooms in the first year of the study but showed higher levels in the summer of the second year.

Orbost Bacterial

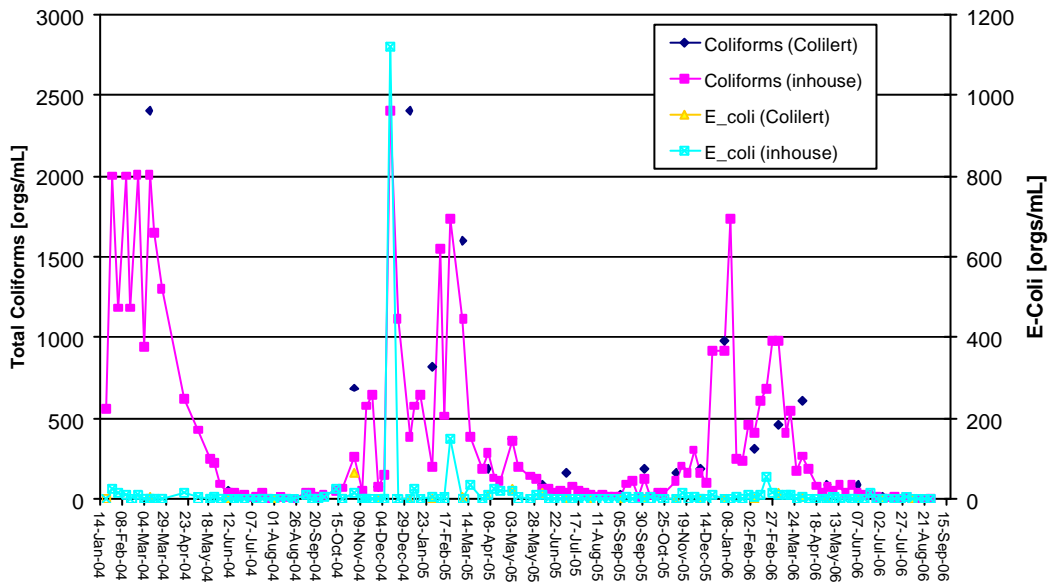


Figure 26. Orbost Bacterial test results.

Bacterial levels at Orbost showed a strong seasonal effect perhaps due to the presence of water birds and warmer water. While not strict controls, the presence of similar or higher

levels of algae and bacteria in the uncovered basins during the second year of the study suggests that the reduced levels in the covered basins are not just seasonal variations. This is reinforced by the similar weather and water conditions for the two years of the trials.

Evaporation

The evaporation rate was estimated to have been reduced by at least 90% by the covers. A bulk aerodynamic model was used to estimate free surface evaporation where a fitting parameter was calculated for each site based on measured pan evaporation rates. This was then used to calculate the basin evaporation rates using the atmospheric measurements made on the water at each basin. Evaporation from covered basins was estimated from measurements of moisture vapour pressure gradients on both sides of the covers.

Evaporation rates were calculated using equation (1) [1]

$$E = k U_o (V_{\text{sat}} - V_p) \quad [\text{mm/day}] \quad (1)$$

Where k is a constant dependant on the site and the air speed at the water surface is $U_o = U(h) \ln(h/Z_o)/\ln(8.0/Z_o)$ and $U(h)$ is the wind speed at height h , V_p is the water vapour pressure in the air [mbar], V_{sat} is the saturated vapour pressure at the water surface, and Z_o is the roughness scale length in metres for the ground or water surface over which the air is passing. V_p is calculated from the relative humidity (RH) and air temperature (T) and V_{sat} is calculated from the water surface temperature obtained from the Minisonde data. The empirical equation was derived with an air speed measurement height of 8m and so the pan evaporation was calculated with $U_o = U(1.8) \ln(1.8/0.1)/\ln(8.0/0.01)$ and basin evaporation with $U_o = U(0.4) \ln(0.4/0.01)/\ln(8.0/0.01)$

Z_o over the land was chosen to be 0.1 m and k was adjusted slightly for each site to match the calculated pan evaporation to the average measured pan evaporation with $h=1.8$ m, the height of the land based anemometer. This factor was then used but with $h=0.4$ m, the height of the on-water weather station, for calculation of basin evaporation with $Z_o= 0.01$ m for air passing over the water; previous work [1,2] has shown this to be a reasonable choice. Figure 27 shows the model superimposed on the pan evaporation for Sarsfield.

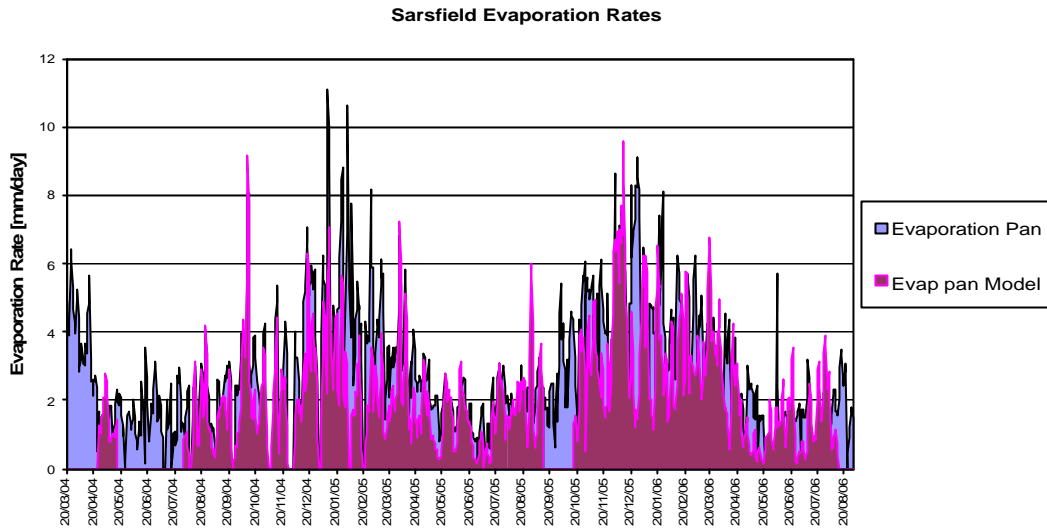


Figure 27. Evaporation pan measurements against model results. Gaps occur where data was not available. The agreement is reasonably good. The parameter k was adjusted to match the measured average pan evaporation from the study period and then the same value used to calculate the basin evaporation using wind speed and water temperature measured over water in the basin.

The results are tabulated in Table 1 below.

Table 1. Evaporation Summary. Evaporation rate estimates without covers.

Site	Daily Evaporation (mm/day)		Annual Evaporation (mm/yr)		Water type	Capacity (ML)	W x L x D (m)	Loss ML/yr
	Basin	Pan	Basin	Pan				
Omeo	2.4	1.8	870	660	Clear	5.2	30x50x3	1.3
Cann River	2.9	2.5	1060	895	Raw	3	30x30x2.3	0.95
Mallacoota	2.8	2.0	1016	725	Clear	22.8	90x110x4.6	10.1
Sarsfield	2.9	2.2	1060	810	Clear	160	80x80x6	6.8
Orbost	2.4	2.1	876	760	Raw	53	55x150x5	7.3
Swifts Creek	2.9	2.8	1060	1025	Raw	4	40x60x3	2.5

These evaporation rates give the expected losses from each basin if uncovered. The last column shows the estimated expected annual losses for each basin due to evaporation when uncovered.

Evaporation after covering

Measurements of the temperature and humidity in the air column between the water surface and the cover were used to quantify the vapour transfer rate between the water surface and the cover. Water vapour will diffuse down the vapour pressure gradients but this flow is much smaller than the moisture transport due to wind. The difference in vapour pressure between the inside of the cover and outside is much smaller than that between the open water surface and the wind. However, this slow diffusion can be more constant than the wind, which may be intermittent. If there is no wind diffusion is still present. Figure 28 shows the RH and temperature 100mm below the cover at three

locations at Swift's Creek. This was collected with free standing USB data-loggers. Figure 29 shows the water vapour pressure calculated from these data and from the outside RH and Temperature at the land weather station nearby.

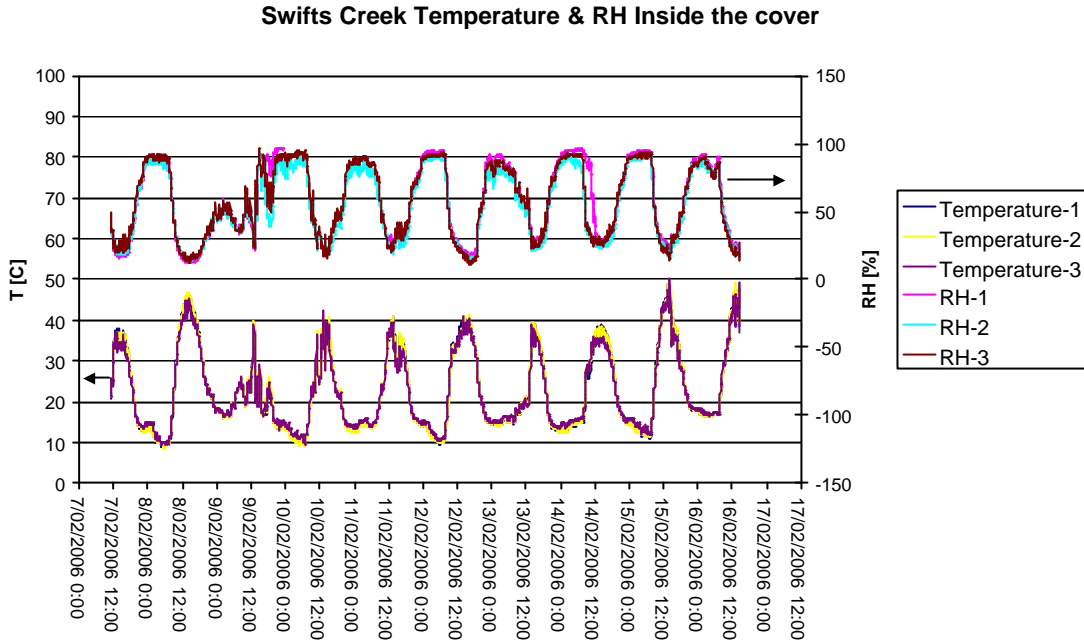


Figure 28. Air Temperature and Relative Humidity inside the cover at Swifts Creek at three locations 100mm below the cover.

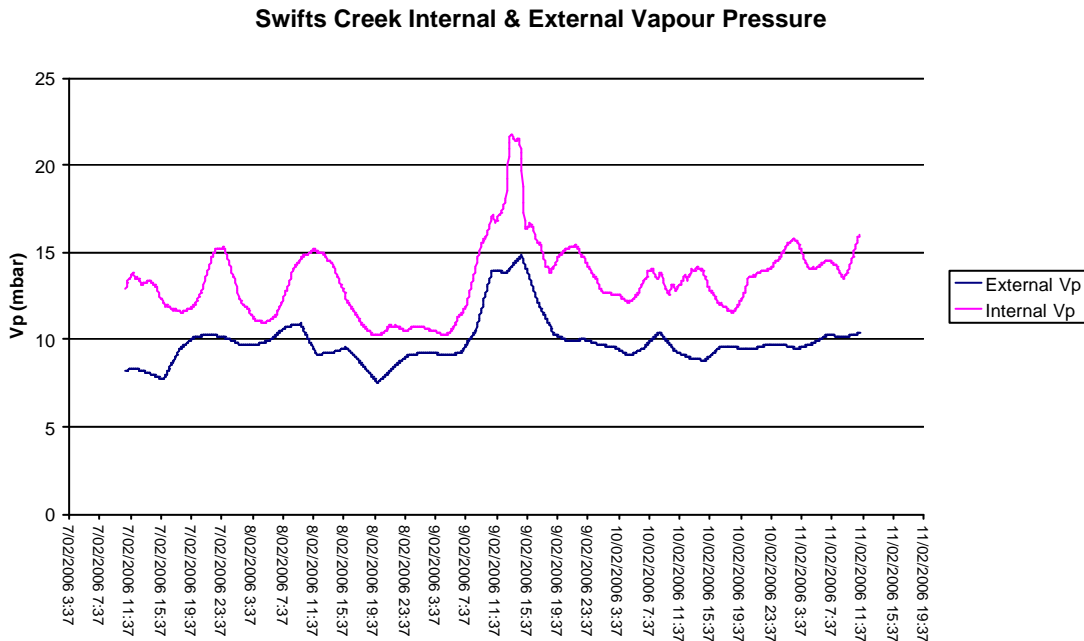


Figure 29. Water vapour pressure (Vp) inside and outside the cover at Swifts Creek. Outside Vp is calculated from the land weather station's Relative Humidity and Temperature.

A calculation of the rate of evaporation is possible using the vapour pressure of the air moving over the surface and that of the air just below the cover using the same equations as for open water and the over-land wind speed. This shows that the “evaporation” rate for the covered basin is about 10% of the uncovered rate but this is a worst case calculation and does not account for the reduction in the diffusion rate by the fabric cover itself, which has an open area of only 2%. Laboratory measurements in free air with no forced air movement and no radiative heating suggest that the diffusion would be reduced by a further 70% by the presence of the shade cloth. Thus it is reasonable to conclude that the evaporation reduction at the basins due to the covers is at least 90%.

Similar data were obtained at Cann River where Relative Humidity & Temperature monitors were positioned at a range of heights above and below the cover. These data suggest that there is a low vapour pressure gradient between 100 mm below and 600 mm below the cover and a small gradient between 600 mm and 1240 mm below the cover (see Figures 30 & 31). Loggers were also later placed 100 mm above, 600 mm above and 100 mm below the cover at the same locations. These results are shown in Figures 32 to 34 below and it can be seen that there is often a positive vapour pressure gradient driving moisture through the fabric but it is much less than that which often occurs between open water and the ambient air. A calculation similar to that performed for Swifts Creek using internal and external vapour pressures, wind speed and constants used for open water evaporation yielded a similar low value for evaporation through the cover even without including low fabric permeability.

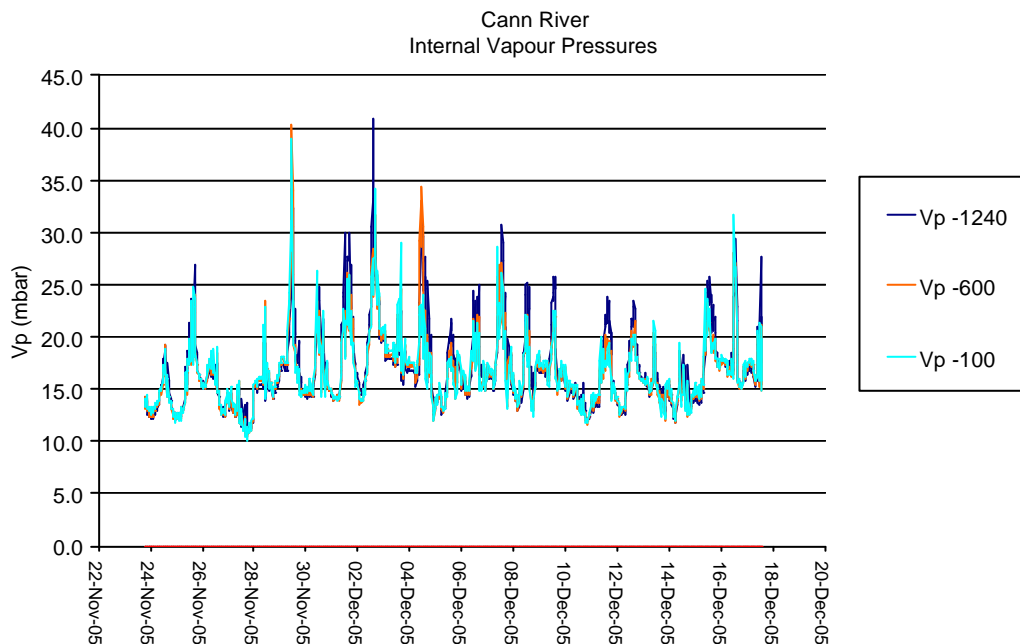


Figure 30. Vapour pressures inside the cover at Cann river, 100 mm below, 600 mm below and 1240 mm below the cover.

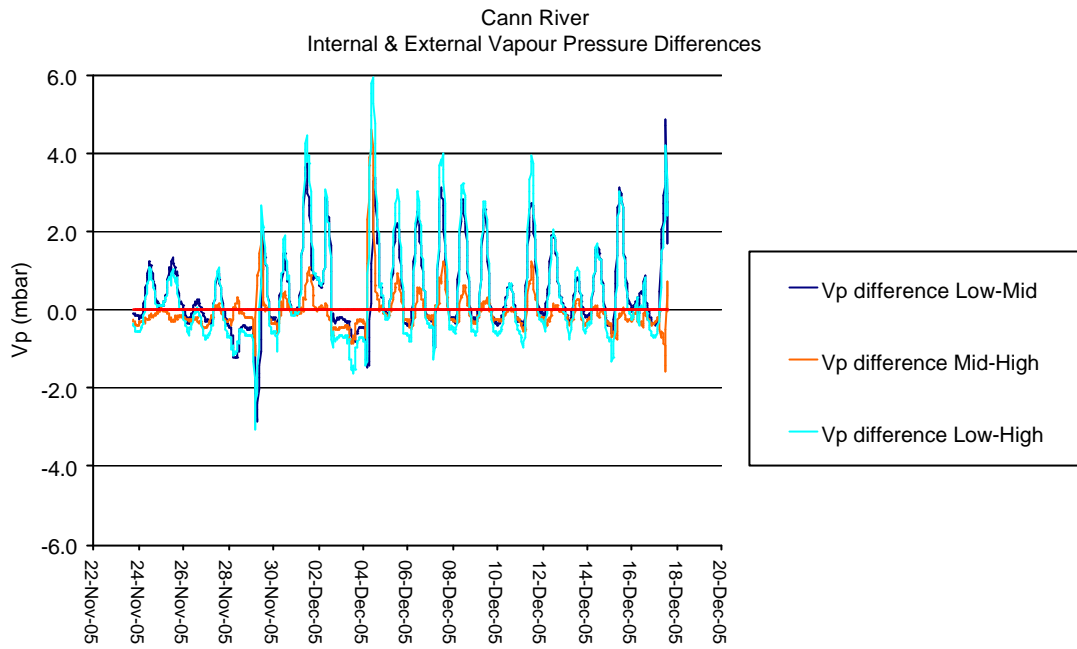


Figure 31. Vapour pressure differences inside the cover at CannRiver, 100 mm below, 600 mm below and 1240 mm below the cover.

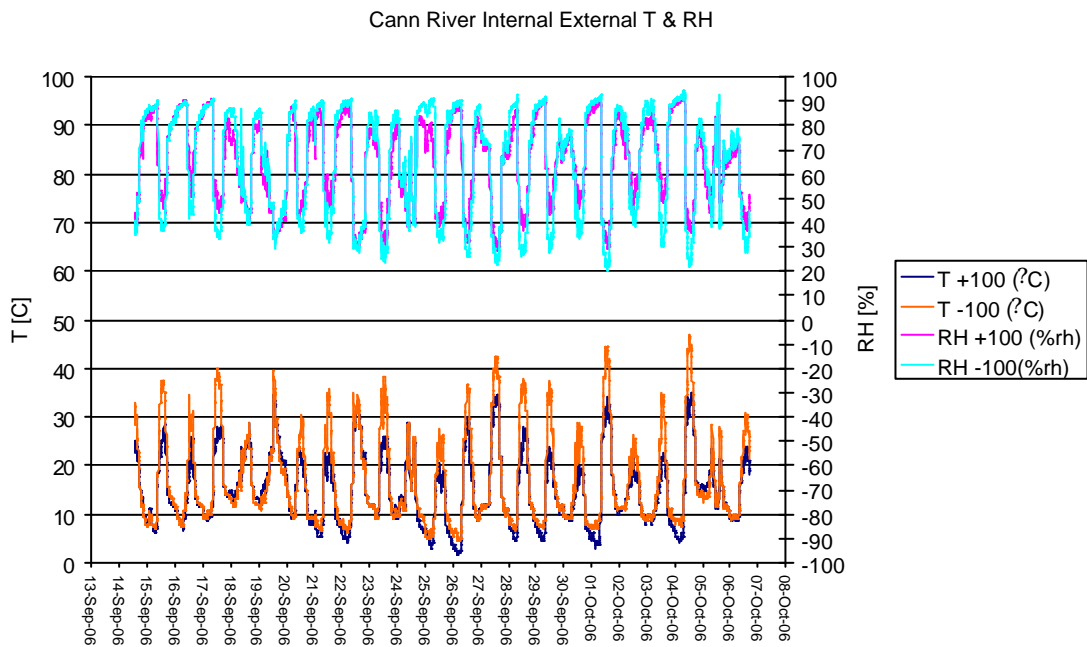


Figure 32. Cann River Internal and External RH & temperature. (+100 denotes above the cover, -100 denotes below the cover)

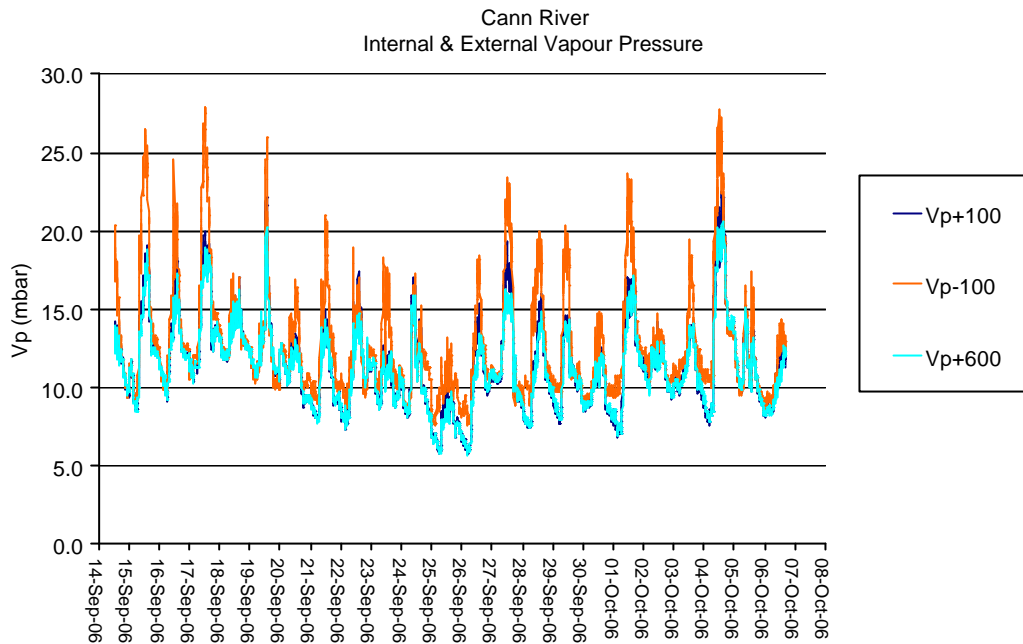


Figure 33. Cann River vapour pressures 100 mm below, inside, and 100 mm and 600 mm above, outside the cover.

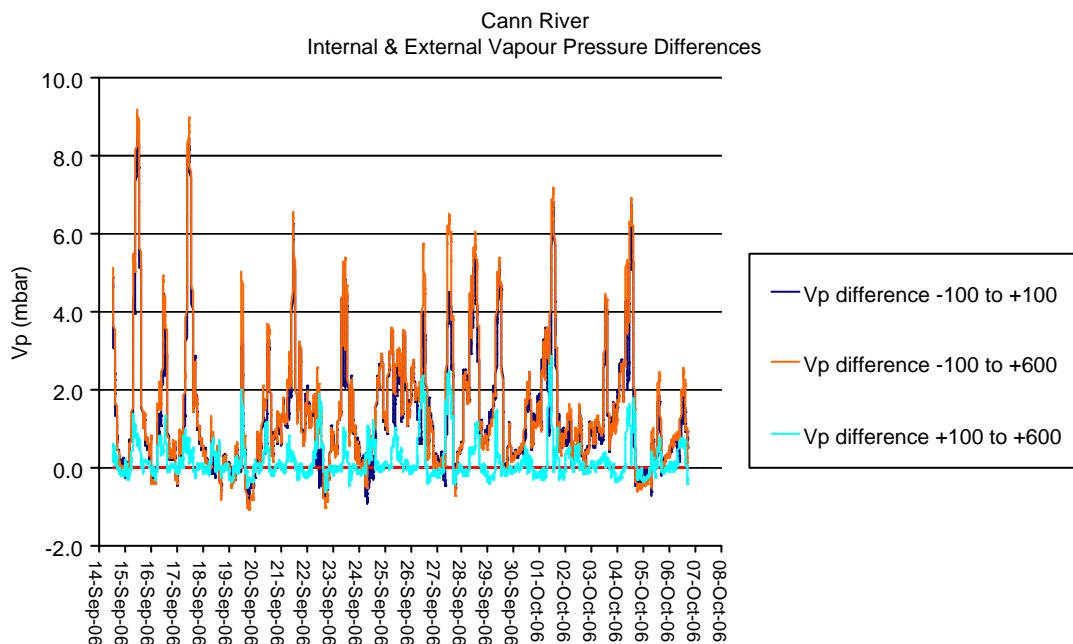


Figure 34. Cann River differences in vapour pressure between the inside (-100) and outside the cover and between close to the cover (+100mm) and well above the cover (+600mm).

Figures 30 to 34 show the vapour pressure gradients down which moisture diffuses from the water surface to the outside. This shows that there are some losses but they are very

small. A calculation of free diffusion results in an equivalent rate of evaporation of about 0.15mm/day compared to several millimetres per day for the wind driven open water situation. A wind driven calculation for the fabric surface vapour pressure difference results in a rate less than 10% of that of the open water situation.

Depth Profiles

In the depth temperature profiles shown in Figure 35 from Cann River the axis shows a depth of 0.0 m at the surface and the water was 1.7 m deep at this time. Before the basin was covered the solar radiation during the day penetrates quite deeply into the water heating the surface layers up to 3 or 4°C warmer than the deeper waters and to a depth of 0.5m or more. The heat is lost during the night through conduction, radiation and evaporation. Although large temperature gradients can be generated in uncovered basins they do not last for long as heat is quickly lost and temperatures equilibrate. Rapid cooling of the surface could also result in a reversal of the temperature gradient that will then result in up-welling of the warmer water and mixing of the layers and can also lift sediments.

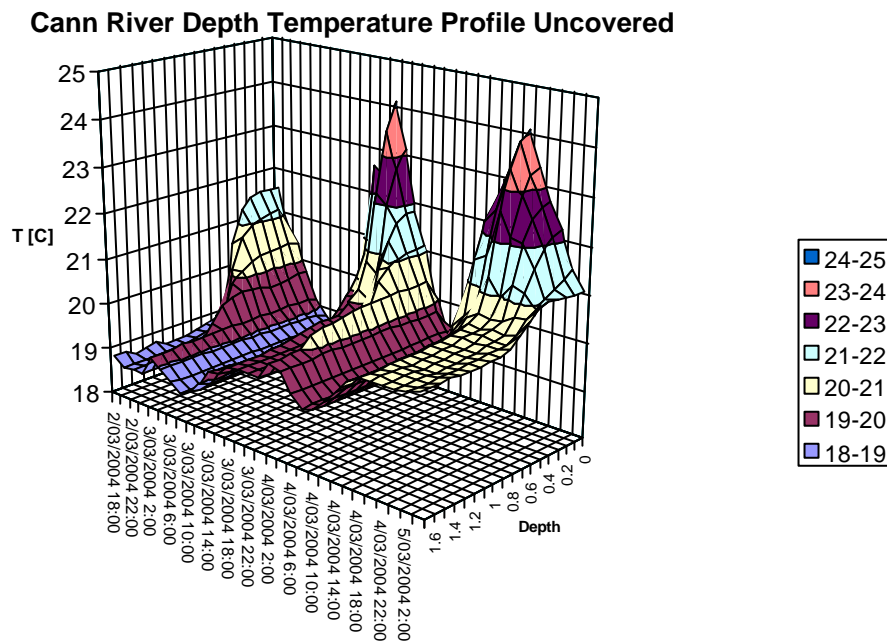


Figure 35. Cann River depth-temperature profiles prior to covering the basin, March 2004.

Cann River Depth Temperature Profile Covered

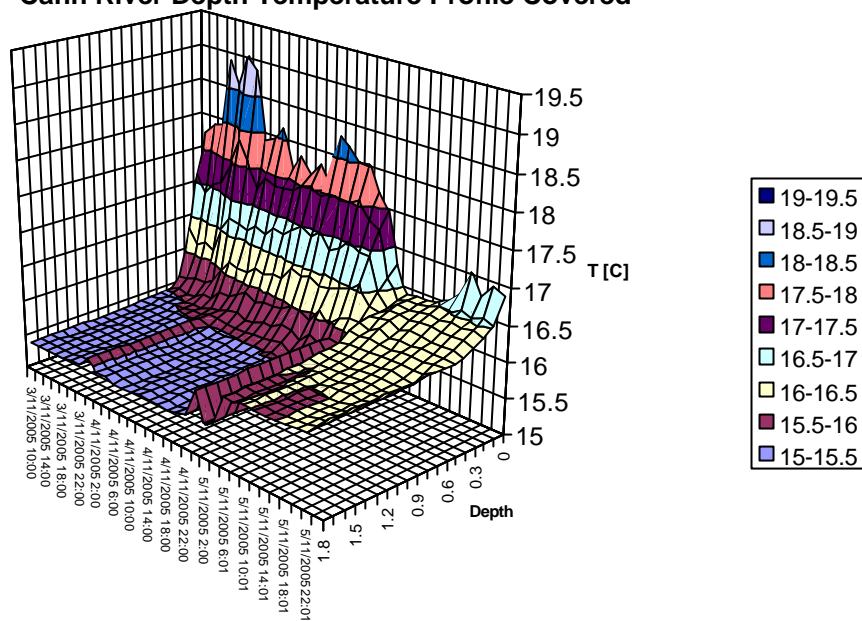


Figure 36. Cann River depth-temperature profile after the cover was installed. The temperature gradient while lower and shallower, persists for several days due to the insulating effect of the cover and reduced evaporation, Nov 2005

Cann River Depth Temperature Profile Covered

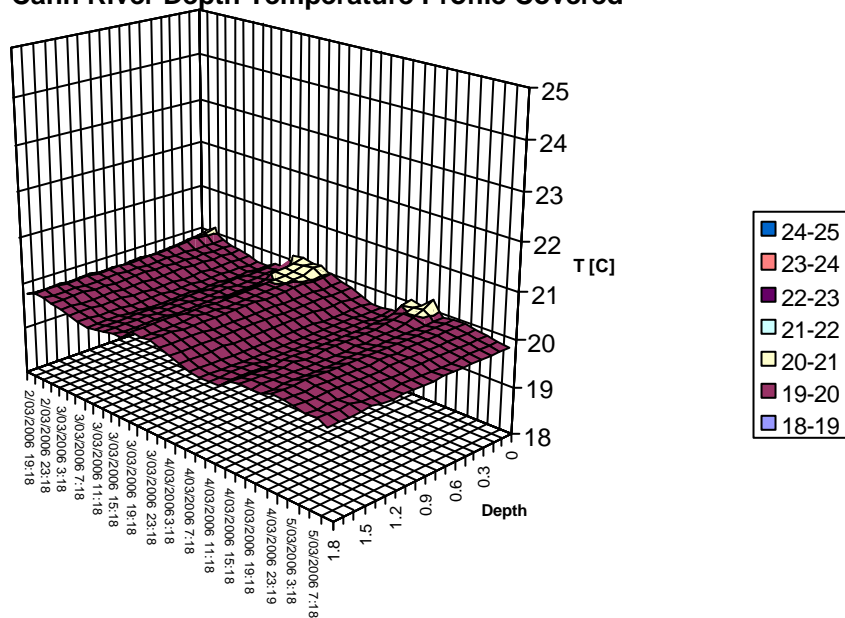


Figure 37. Cann River depth-temperature profiles after covering the basin to be compared with Figure 35 & 36. The basin was being aerated to remove iron contamination and this also eliminated the temperature gradients seen in Figure 35 & 36. It will be seen that other covered basins when not aerated (un-mixed) also display temperature gradients, e.g. Figure 39, and they last longer than when uncovered.

The periods of time for the depth profiles of covered basins were chosen for similar weather conditions to the uncovered examples shown. When the basin is covered with shade cloth (e.g. Figure 36 for Cann River and Figure 39 for Swifts Creek) the direct radiation is reduced by approximately 98% and the water is only heated by the residual direct radiation, radiation from the heated fabric, and conduction and radiation from the heated air under the cover. The cover also provides some insulation and prevents evaporation reducing the heat losses. The water therefore remains slightly cooler under the cover and while temperature gradients are smaller they can be more stable and longer lasting. After covering at Cann River a problem arose with iron contamination being pumped from the primary water source, a local river. The cold contaminated inlet water sank as it was fed into the basin and formed a layer of high iron content water at the bottom that was not readily oxidised. To remove this problem an aeration system was installed that mixed the water with high efficiency and resulted in efficient aeration at the surface. This also served to remove temperature gradients (Figure 37) although they were not contributing to the iron problem.

Figures 38 and 39 are depth profiles for Swifts Creek again showing that when the basin is covered the temperature gradients are more stable and do not dissipate as rapidly as when uncovered. Since a large component of the cooling is evaporation this may constitute significant water saving but could also lead to undesirable stable stratification of the water body. However, the temperature gradients observed only lasted for a few days and when the weather cooled the temperature profile levelled out and the water temperature dropped. If temperature stratification were to become a problem then it is readily solved by mixing the water using submerged piping and compressed air as was done at Cann River. Other means of mixing the water can also be employed, which can also serve to aerate the deeper water. The main problem with a stratified water body is that a very cold anoxic layer can form at the bottom of the storage. However, this usually only occurs in deep basins. Layering occurred diurnally in uncovered basins and more stably in covered basins but this difference is not sufficient to conclude that stratification would be more problematic or prevalent in covered basins than in uncovered basins. Turnover events can also occur in water storages whereby the water body is heated to some depth but a cold snap then rapidly cools the upper layers and the warmer submerged water rapidly comes to the surface causing turbulence that may disturb sediments causing turbidity problems. One effect of the cover is to slow down the speed with which water temperature changes occur and so this type of undesirable event is unlikely to occur in a covered basin.

Swifts Creek Depth Temperature Profile Uncovered

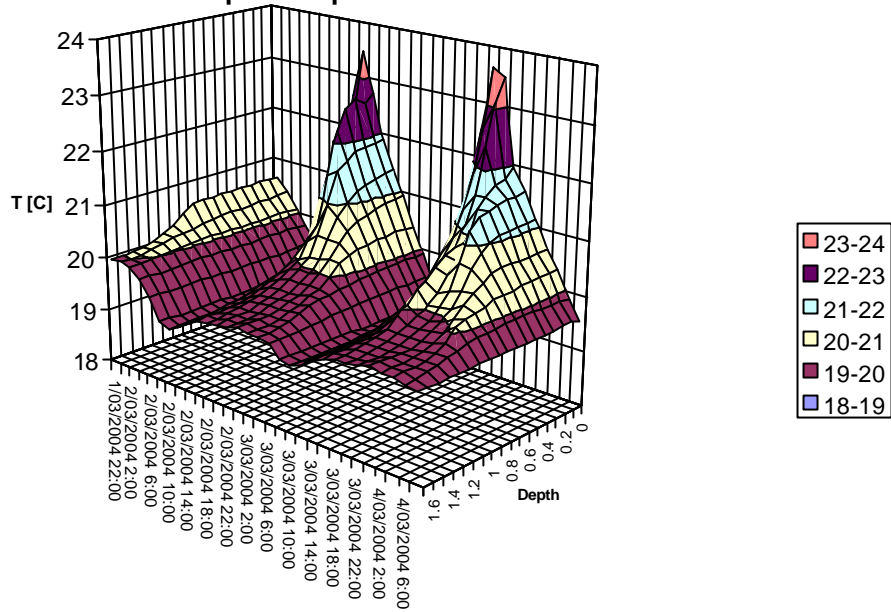


Figure 38. Swifts Creek Depth-Temperature profile before covering, March 2004.

Swifts Creek Depth Temperature Profile Covered

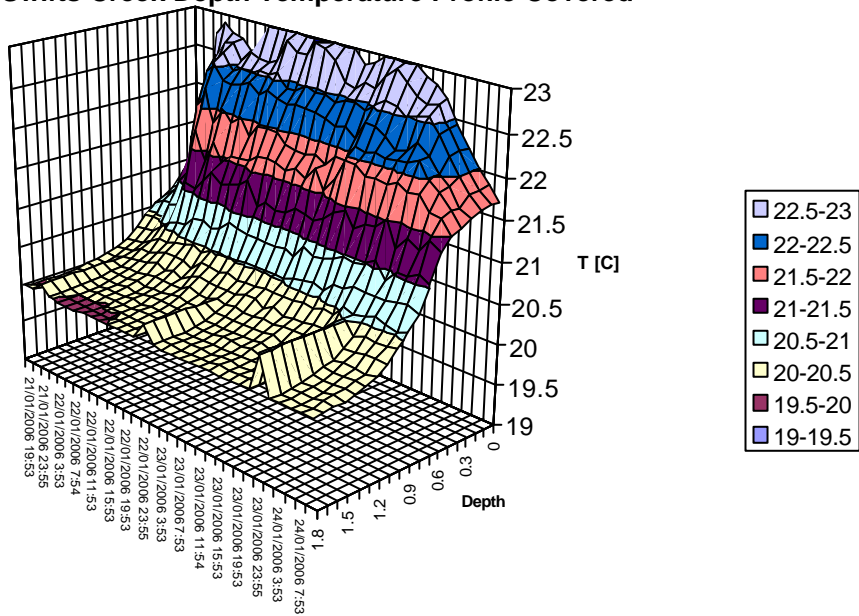


Figure 39. Swifts Creek Depth-Temperature profile after covering, January 2006. Note that the temperature gradient doesn't disappear over night as it does in an uncovered basin.

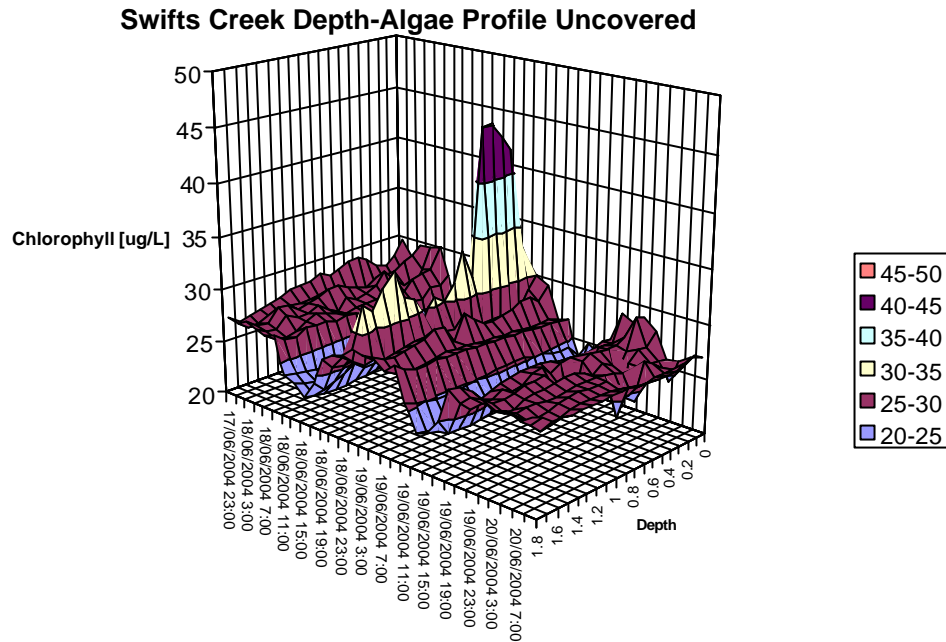


Figure 40. Swifts Creek Depth-Chlorophyll profile, uncovered, June 2004.

In Figure 40 the variation with depth of the chlorophyll signal during an algal event can be seen. A peak occurs for a short period near the surface but generally the algae appear to be quite evenly distributed through the water. Extremely brief and localised peaks were also occasionally observed at the surface but may have been due to floating debris or clumps of algae.

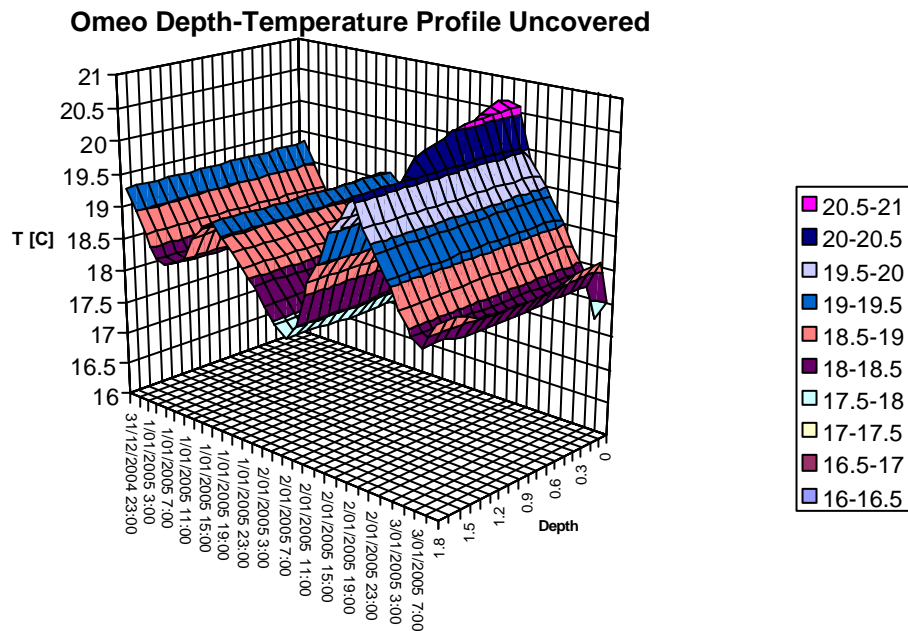


Figure 41. Omeo Depth-Temperature profile uncovered, December 2004 to January 2005.

Omeo Depth-Temperature Profile Covered

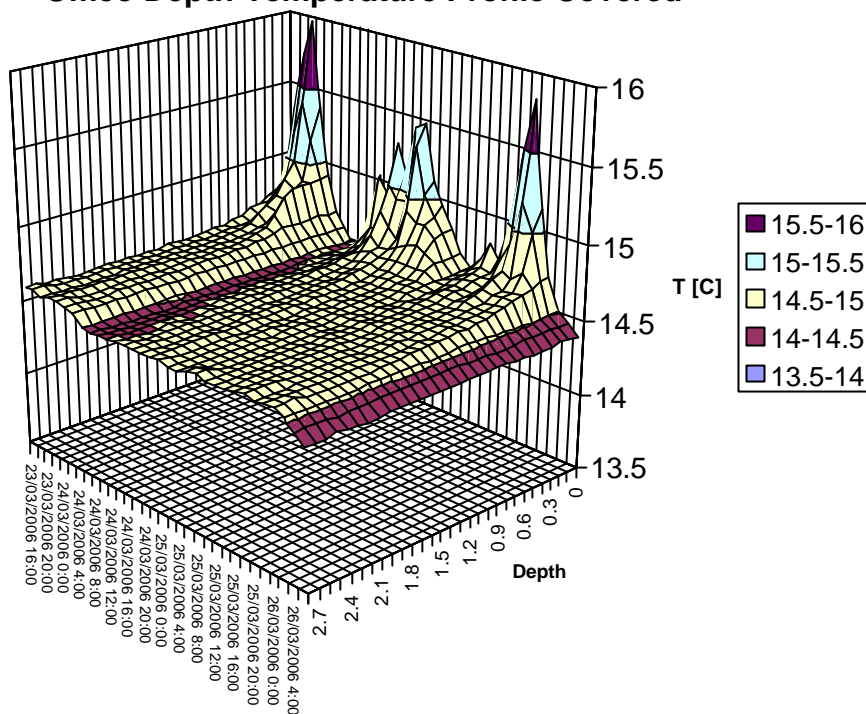


Figure 42. Omeo depth temperature profile after covering, March 2006.

Omeo Depth-Algae Profile Uncovered

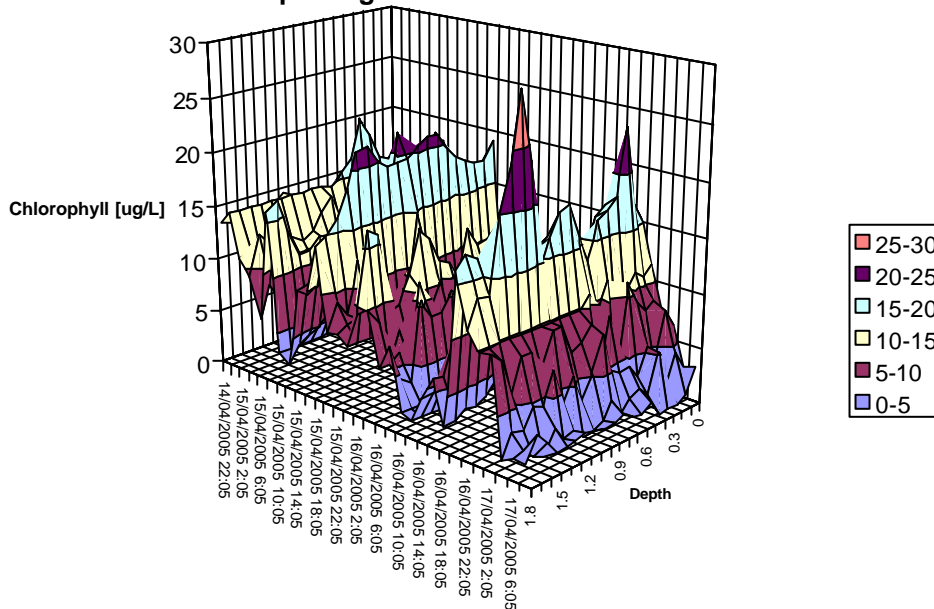


Figure 43. Omeo Depth-Algae Profile, April 2005.

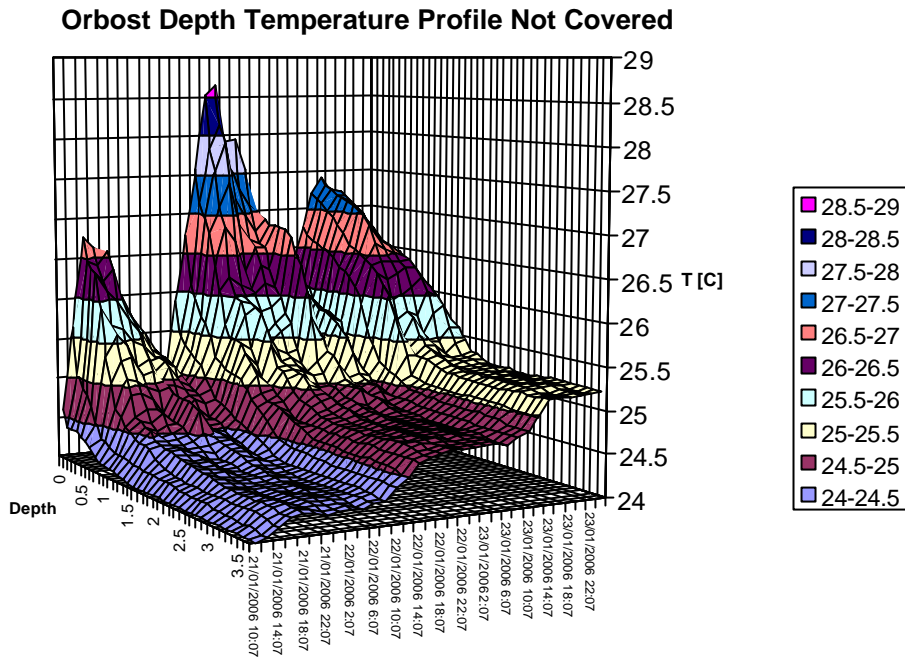


Figure 44. Orbost Depth-Temperature profile.

The depth-temperature profile from Orbost in Figure 44 shows how the temperature of the water body rises due to radiative heating at and near the surface with absorption falling roughly exponentially with depth. Heat then conducts slowly down into the deeper water.

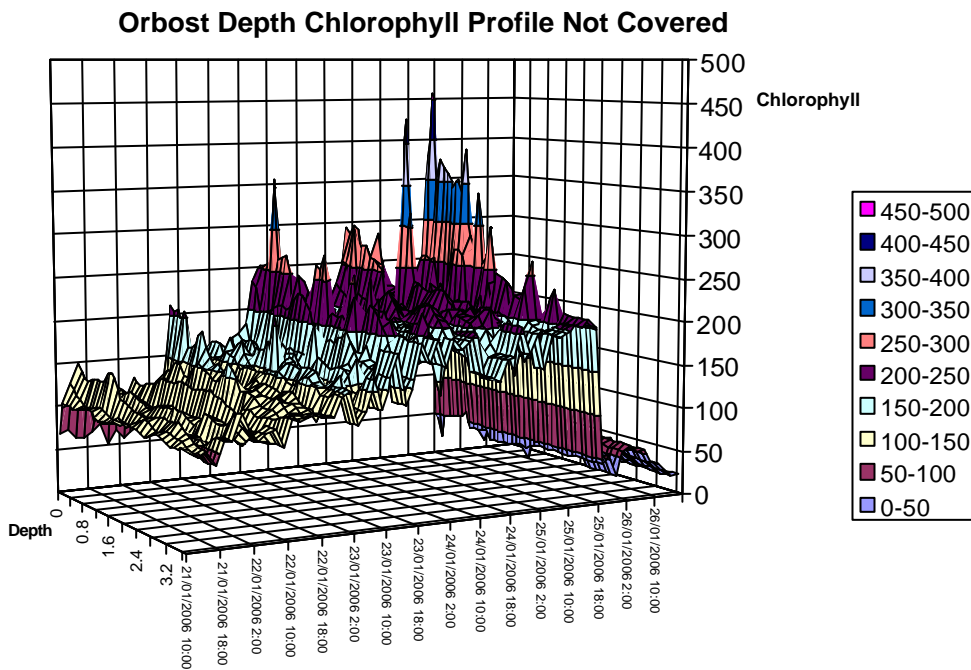


Figure 45. Orbost Depth-Chlorophyll profile January 2006.

Figure 45 shows the distribution of growth of an algal bloom at Orbest over six days in January 2006, the same time period as for Figure 44. The figure shows higher growth at the surface and the sudden dying out of the bloom 25 January. This event is also seen in Figure 24 in both the Minisonde chlorophyll signal and the laboratory test results.

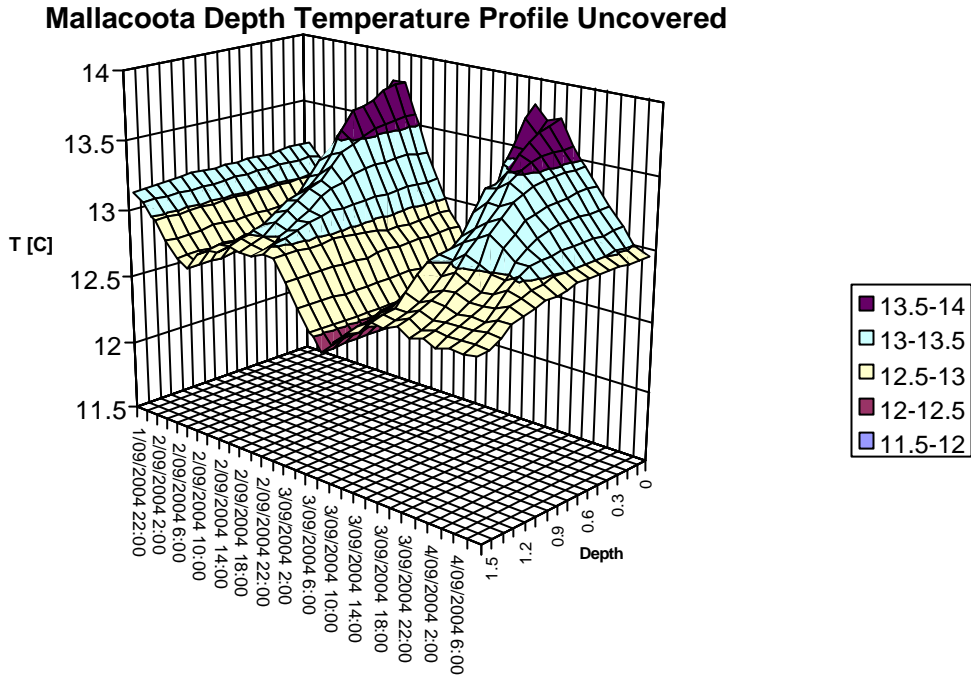


Figure 46. Mallacoota depth temperature profile before cover was installed

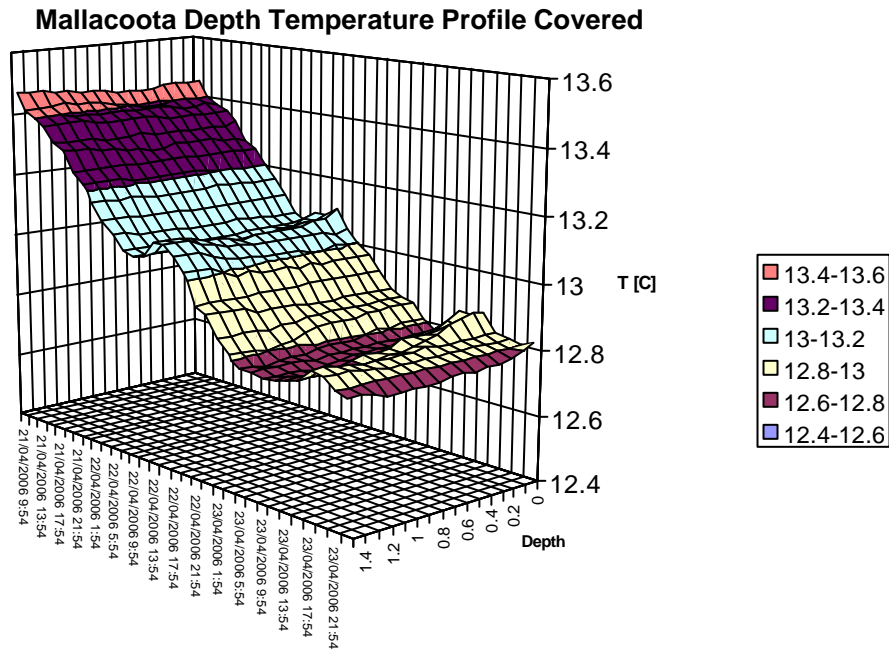


Figure 47. Mallacoota depth temperature profile after cover was installed.

Sarsfield Depth Temperature Profile Not Covered

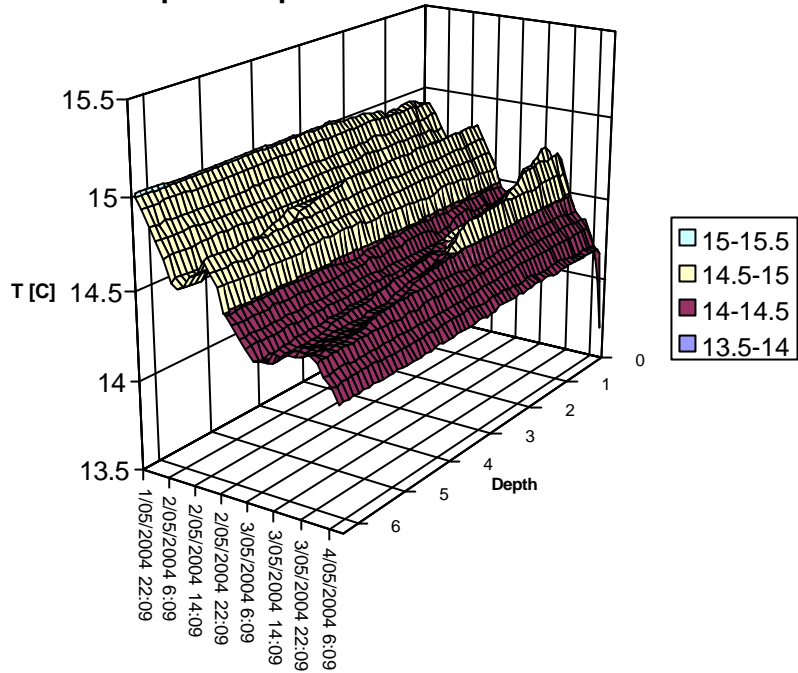


Figure 48. Sarsfield Depth-temperature profile. Sarsfield is the deepest basin at 6.5 m.

Sarsfield Depth Chlorophyll Profile

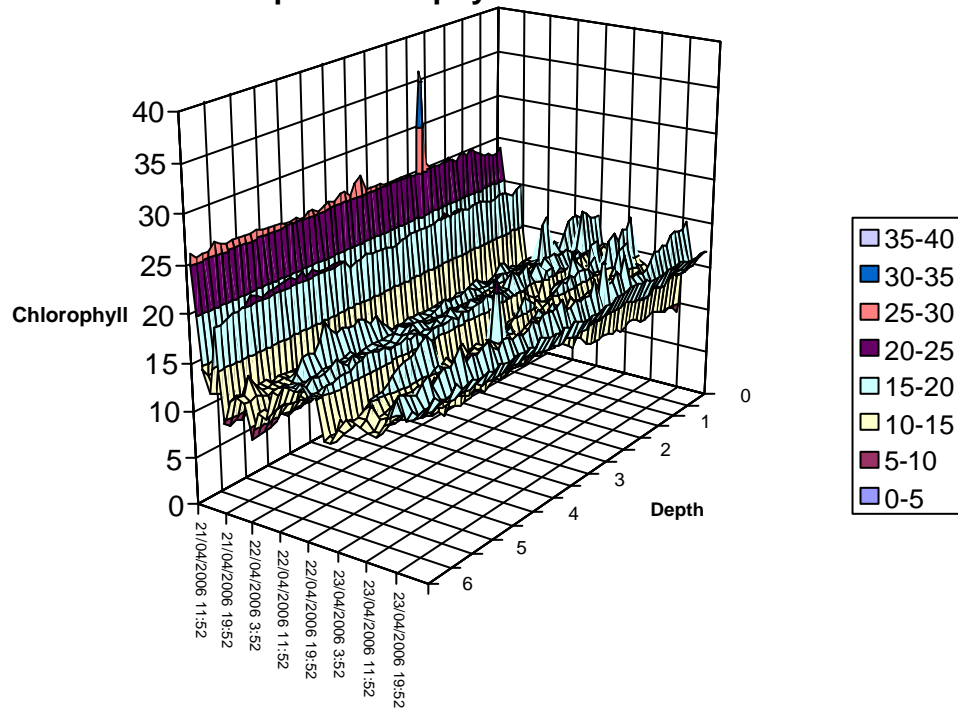


Figure 49. Sarsfield Depth-chlorophyll profile.

Shade-Cloth Structures

The covers for the basins are tensioned architectural structures designed and installed by Superspan. The fabric used in the structures was Commercial 95 shade cloth manufactured by Gale Pacific. A tented structure design was used at the basins to allow for access to the water surface at the request of East Gippsland Water. However, a flat structure design can also be used and this would have lower installation costs.

The covers were suspended from steel cables from galvanised steel posts bolted to concrete footings. The steel structural components have fared well so far except for one failure at Omeo due to heavy snow (see Figure 50 below) and the use of a low quality chain because of a local availability issue. The chain failed when the cover was heavily laden with wet snow. The cover suspension system would not be expected to fail when the usual components are used.

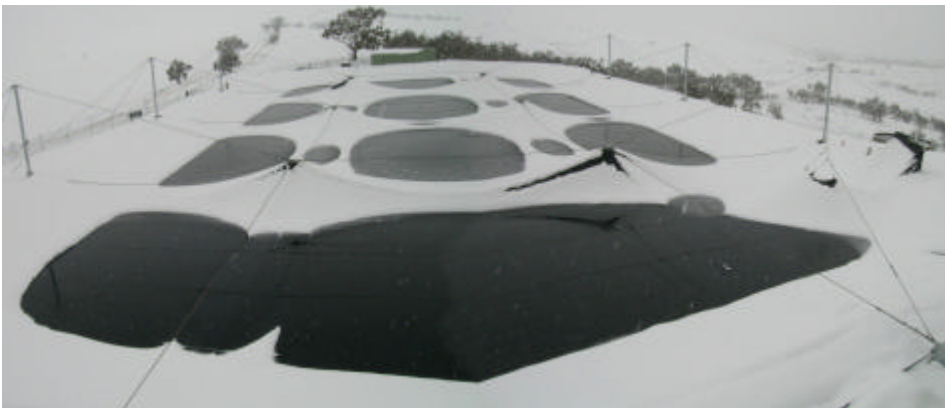


Figure 50. *Omeo after a heavy snow fall*

The anchor design for the covers was modified after observing the damage caused to the fabric by repeated contact with the rock beaching on the basin banks at a pre-trial site. The need for a close fitting skirt to reduce evaporation and prevent the entry of debris was clearly demonstrated in the months just following cover installation before a skirt was designed and attached to most of the basins. Further improvements could however still be made in this area as the skirt design at Swifts creek failed and holes continue to be made in the fabric at some sites due to contact with beaching rocks and jetty railings under the covers. Removal of beaching near the top of the banks prior to covering is recommended.

Related to the problem of fabric damage is the need for correct structure tensions to be maintained and to prevent contact between the fabric and basin beaching and with structures such as hand rails and doorways. An improved tensioning method that local staff can readily implement may assist in the ease of maintenance and prevent damage from occurring.

It appears a redesign of the access would be of benefit to EGW staff, as the entrances are not high enough to walk under, and the fabric has torn away from the door arches at

Omeo and Swifts Creek on several occasions requiring repairs. Cable ties were used but are unsuitable in the long term, either tearing through the fabric or themselves breaking due to UV degradation.

The problems with the covers discussed here are, however, minor issues compared to the successes seen since their installation. Omeo has withstood very high winds and heavy snow falls and no significant algal blooms have occurred in covered basins through the past summer. Bacterial counts have also been greatly reduced and seem now to relate entirely to pumping events at the Raw Water Storage basins (Cann River and Swifts Creek). At Mallacoota there is an ongoing problem with Diatoms (*Synedra* sp). These appeared to thrive in the Clear Water Storage even under low light conditions, possibly due to the levels of silica present in the storage that served as 'building blocks' for their silica 'shell'. This hard silica shell can cause problems in a water treatment plant by adding to filter blockages and increasing backwash operations. Increased backwash cycles increases the amount of water 'wasted' at the plant and lowers the volume of water produced. It may be possible to filter them out at the inlet to the basin and the outlet to the treatment plant. Filtering of inlet water at raw water storages could possibly allow the benefits of the covers to be more fully exploited, as they are at the clear water storages.

At two sites it became necessary to install a means of mixing the basin water following the pumping into the basin of water with high iron concentrations (Cann River and Swifts Creek). There is concern that stratification due to high and stable surface temperatures after covering could create a zone of cold and possibly anoxic water at the bottom of the basin causing potential problems during water treatment. The temperature-depth-time profiles obtained prior to covering suggest that the problem is only slightly worse after covering than it was before.

A vein aeration pump and relatively simple plumbing has achieved the necessary mixing at Cann River and Mallacoota though it is likely that less energy could be expended by ensuring the most efficient method and timing of mixing is used. Through monitoring a basin's temperature profile it would be possible to implement active mixing only when stratification occurs.

Further work by modelling or measurement could be done to calculate the relative costs of different mixing approaches (eg. varying bubble size and quantity, heating, agitation).

The relationship between pH fluctuations and algal activity could lead to a more robust method of detecting rapid growth of blooms earlier and more cheaply than the current fluorometer.

The Mallacoota Clear Water Storage, Cann River Raw Water Storage and Swifts Creek Raw Water Storage were videoed using remote controlled robotic camera to assess the amount of aquatic plant growth. These storages were videoed in March 2004, (before covers were installed), and again in November 2005 and March 2006 (after covers had been in place for a number of months). Before cover installation, the aquatic plant growth in the Swifts Creek storage was so prolific that it was decided to remove as much material as possible to avoid potential water quality deterioration through excess nutrient

and bacteria levels caused by rotting vegetation. The videos before and after covering showed that no re-growth of aquatic plants had occurred except in small areas where light leaked through openings in the covers, which can be readily remedied. Long term monitoring of plant populations will continue through visual inspection.

Conclusions

This study has shown that the incidence of algal blooms is dramatically reduced by the presence of the shade cloth covers. In the case of the Omeo clear-water basin the cover has prevented algal growth to such a degree that the basin can be used reliably as weekend supply in summer for the first time ever; this has reduced labour costs significantly. Water birds can no longer access the basins though occasionally small birds and animals still enter through remaining openings. Wind-borne organic materials have less opportunity to enter the water storages. Plants no longer grow at the bottom of the basins because of the lack of light, reducing maintenance costs. In the case of raw-water storages the frequency of adverse bacterial events was not as greatly reduced as for treated water storages. This is because raw-water storage contamination is usually the result of pumping from contaminated sources. In the case of treated-water storages the incidence of adverse bacterial events is greatly reduced. This should lead to a reduction in the amount disinfection required prior to entry into the reticulation system. Minor chlorophyll events occurred at the raw water storages after covering, these were due to pumping in of contaminated water. However, the algae introduced into these storages did not readily multiply / grow due to the lack of light. Since covering the basins no remedial action with respect to algae, such as algaecide dosing or draining of the basin, has been required.

The chlorophyll fluorometers sometimes suffered from direct contamination by algae. The fluorometer contamination reduces confidence in the absolute chlorophyll values but the results are still valuable providing continuous data with a fine time scale and depth resolution. The chlorophyll measurements were always backed up by manual sampling and laboratory identification and counting. It was also observed that algal blooms are often accompanied by strong diurnal oscillations in pH. A preliminary study of these results suggests that diurnal oscillations in pH could possibly be used as a lower cost monitor for algal activity in water storages.

The air speed under the covers is effectively zero when the basins are covered and skirts are properly fitted and so normal turbulent surface evaporation isn't possible. Evaporation from covered basins was estimated to be less than 10% of normal evaporation. This is due to the zero wind speed, stable air temperature profile, lower water surface temperature under the cover, the cover permeability, and reduced vapour pressure difference at the interface. In the uncovered case the interface is the open water surface where the vapour pressure is at saturation. When the basin is covered the interface is at the fabric surface and the internal vapour pressure is much closer to the external vapour pressure and diffusion is reduced by the fabric.

The rate of evaporation was measured with an evaporation pan at each site. The evaporation from the basin was calculated using the weather data measured by the floating weather station on the water. A fitting parameter was adjusted to predict the measured annual pan evaporation rate and then this parameter was used in the calculation of basin evaporation using the weather data obtained on the water. Annual evaporation rate estimates ranged from 870 to 1060 mm per year. At Mallacoota, the largest covered basin, the estimated evaporative loss is equivalent to 8.5 ML of water per annum. Pan evaporation rates ranged from 660 to 1025 mm across the sites.

Some practical design issues occurred with the covers and support structures themselves, including abrasion against rock-beaching and objects under the covers, and problems with the entrances and skirts. These will be rectified by the structural engineers and improvements incorporated into future designs.

Temperature stratification of the water column was shown to occur at various times in both covered and uncovered basins during hot weather. The temperature gradients appear to be more persistent in covered basins due to reduced evaporation and hence reduced evaporative cooling and to the insulating effect of the covers. Where the stratification causes quality problems, for covered or uncovered basins, mixing can be achieved by several simple means. During this study mixing was achieved by aeration using submerged perforated plastic piping and a high pressure blower.

The improved water quality and massively reduced risk of algal blooms and other contamination provided by the covers offers a valuable enhancement in security of water supply. Maintenance costs with respect to aquatic plant growth are also expected to be reduced. Evaporation reduction, while not the primary motivation for covering basins, is highly significant and in circumstances where alternative water supplies are not available, potentially valuable.

Shade cloth covers are expected to have advantages over alternative covers in terms of costs, maintenance, and ease of operation. Sealed suspended covers carry a risk of growing biofilm on their moist inner surfaces and because they block 100% of the light and seal in gases they pose potential health and safety risks for operators when working inside them. Floating covers require drainage infrastructure for rain capture and also grow potentially problematic biofilms on their inner surfaces. They also do not allow staff access or readily allow visual assessment of the water storage.

References

- 1 Webb E.K., "Evaporation From Lake Eucumbene", CSIRO Publications, 1960
- 2 Pauken, Michael T., "An experimental investigation of combined turbulent free and forced evaporation" Experimental Thermal and Fluid Science 18 (1999)

Photos

- | | |
|----------------|---------------|
| Cover, 1,2 & 4 | Scott Barnes, |
| Photo 3 | Terry Watt |

Acknowledgements

This project was a collaborative effort involving CSIRO, Gale Pacific, Superspan and East Gippsland Water. Valuable contributions were made by the management and staff of all these organisations for which the authors are extremely grateful. In particular we would like to thank Kristine Hunter, Selina Mok, Elizabeth Cigulevski, and Stuart Cannon.