Lake Trevallyn
Algal Monitoring data analysis
2007/8 and 2008/9

E300382-2
12 February 2010

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<td>E300382-2</td>
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<td>Project reference</td>
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## Revision history

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### Revision 2

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Executive Summary

The cyanobacterium (blue-green alga) *Anabaena circinalis* was first detected in Lake Trevallyn in bloom proportions in January 2007 and persisted for several months. This prompted the establishment of a comprehensive weekly monitoring program that collected data over the summer and autumn months (the “bloom season”) during 2007/08 and 2008/09. The aims of the program were to quickly provide stakeholders and the public with information on the water quality status of Lake Trevallyn, and to provide a set of quality data that would be useful in the interpretation of the drivers of the bloom in Lake Trevallyn to assist in future management.

Analysis of the first two seasons of data (2007/08 and 2008/09) is undertaken in this report. *Anabaena* blooms occurred in both seasons monitored, but were characterised by differences in their size, timing and persistence. In 2007/08, *Anabaena* was present for at least four months (January-April) and often at high cell concentrations; in 2008/09 it was first detected later in the season, was present for two months (March-April) and high cell concentrations were short-lived.

The occurrence of thermal stratification was evident in Lake Trevallyn in both seasons, and tended to be stronger in 2007/08. This appears to be a significant factor in the development of blooms in both seasons, and is likely to be an essential factor driving blooms in Lake Trevallyn. Higher water temperatures early in the season in 2007/08 may also have been a factor that increased the competitive ability of *Anabaena* early in the season to assist in establishing the bloom.

There is some evidence that lower water residence times in Lake Trevallyn inhibit the development of *Anabaena* blooms in the upstream portion of the lake by reducing the depth and persistence of temperature stratification. This provides some evidence that low flows favour stratification and promote the occurrence of blooms in Lake Trevallyn.

It appears that phosphorus is most likely to be a limiting nutrient. There is some evidence that inflows deliver sufficient phosphorus to establish and maintain blooms, with bloom initiation tending to coincide with increased in detectable dissolved phosphorus concentrations.

Following this analysis, the general hypothesis for the drivers behind bloom formation is:

- to establish a bloom it is necessary for strong and persistent thermal stratification to occur in the presence of a source of dissolved phosphorus. These conditions provide buoyant *Anabaena* with an advantage in gaining access to light, allowing it to grow faster and out-compete other species for the limiting nutrient resource;
• high water temperatures of approx 20°C (which tend to co-occur with strong thermal stratification) may be necessary to allow *Anabaena* to grow at a rate sufficient to establish dominance;

• if these conditions occur early in the season and a bloom of *Anabaena* establishes itself, it is likely it will persist and fluctuate in response to the physical conditions and available nutrients until temperature and mixing conditions become unfavourable in April.

It is recommended that the monitoring program continue in Lake Trevallyn to provide further understanding and evidence of the drivers of blooms in Lake Trevallyn. Refinements to the program are recommended including the removal of unnecessary analyses and the installation of a thermistor chain to track stratification on a shorter time-scale. Methods of destratification should be investigated in some detail to determine the effectiveness and potential benefits that these may provide.
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1. Introduction

1.1 Purpose of document

The main purpose of this document is to provide analysis of algal monitoring data collected from Lake Trevallyn for the summer/autumn periods of 2007/08 and 2008/09.

This document provides:

- An overview of the current monitoring program and its purpose;
- Detailed analysis of the available algal, nutrient, physical and chemical data collected during monitoring, with the aim of identifying drivers of *Anabaena circinalis* blooms;
- Proposed monitoring program for 2009/10 and beyond; and
- Mitigation options to be considered in the future.

1.2 Background to blooms in Lake Trevallyn

The cyanobacterium *Anabaena circinalis* was first discovered in Lake Trevallyn in bloom proportions in January 2007 and persisted until May 2007 (Figure 1). In this year there was no formal monitoring program established. The main impact of the bloom in this first occurrence was that it provided taste and odour compounds in drinking water. It was also the cause of human health concerns surrounding the possible presence of *Anabaena* in proportions considered to cause potential harm to recreational users and required the relocation of a major recreational event planned for Lake Trevallyn during the bloom. The bloom was found to be non-toxic, posing a lower risk to the values of the lake (recreational, drinking water supply, environmental) than a toxic bloom.

Local government, government agencies, and business organisations took appropriate action at the time of the bloom. West Tamar Council, Meander Valley Council and Launceston City Council installed appropriate signage around the lake to inform the general community of the primary and secondary risks associated with the bloom for its duration. Department of Health and Humans Services issued health warnings. Esk Water commenced treatment of source (raw) waters with powder activated carbon (PAC). Hydro Tasmania maintained the lake levels in Trevallyn to reduce the likelihood of surface waters, with high cell densities, entering the water treatment plant. Some low level monitoring was undertaken during January-May 2007 period, however this was reactive monitoring which served to provide answers to an immediate problem.
A more comprehensive monitoring program was proposed, supported and funded by stakeholders (NRM North, Hydro Tasmania, Esk Water [now Ben Lomond Water], West Tamar Council, Meander Valley Council, Department of Health and Human Services, DTAE, DPIW [now combined as DPIPWE]) and was also instigated in time for the following summer. The monitoring program had two aims:

1. To provide up-to-date information to stakeholders and the public as to the status of the bloom in relation to the risks it posed; and

2. To gather data to aid in identifying the processes that both trigger and drive blooms of *Anabaena circinalis* in Lake Trevallyn

To date there have been two seasons of monitoring undertaken, and additional stakeholders (Parks and Wildlife Service [part of DPIPWE], Launceston City Council) have become involved in the program. With three years of experience, stakeholders are now very familiar with their respective requirements and procedures to deal with the occurrence of a bloom.

With two monitoring seasons of good quality data, it is now the aim to examine available data in greater detail to develop a better understanding of the factors that may be influencing the blooms of *Anabaena circinalis* in Lake Trevallyn. During the two years of the coordinated monitoring program, 2007/8 had a significant bloom, whereas 2008/9 had very little presence of *Anabaena circinalis* until later in the season, when there was a moderate sized, but short lived bloom. These differences between the blooms in the two monitoring seasons will be used to compare the different influences in the two years.
2. Monitoring overview

2.1 Lake Trevallyn

Lake Trevallyn is a run-of-rivers hydro-electric storage located on the lower South Esk River (Figure 2) that has its water directed to Trevallyn power station. It is approximately 6 km long, rarely wider than 200 m and has an average depth of around 12-15 metres. Lake Trevallyn has an area of 1.32 km$^2$, a volume of 12,300 ML and is located at the bottom of the catchment, receiving water from an area of 9,535 km$^2$. Three major rivers drain into Lake Trevallyn; the South Esk River, Macquarie River and Meander River.

In addition, a significant amount of water is delivered to Lake Trevallyn from Great Lake, as part of the Great Lake-South Esk hydro-electric scheme. This water travels through the Poatina power station and Poatina tailrace to Brumbys Creek and then to Macquarie River near Cressy.

Lake Trevallyn is a very important as a source of drinking water for Launceston, with the offtake being located at Trevallyn Dam. It is also used extensively for recreational activities including water skiing, kayaking, swimming and fishing. Lake Trevallyn also supports a commercial eel fishery.
2.2 The monitoring program 2007/8 and 2008/9

In the first monitoring season (2007/08), a total of nine sites were sampled (Table 1) which included six “Profile sites” and three “Council sites”. The council sites were reduced to two after the first few weeks of sampling when it became obvious that the phytoplankton assemblage at Hadspen (C3) was very different from all other sites sampled and was unlikely to contain *Anabaena circinalis*. The profile sites (P1-P6) were the most comprehensively monitored sites and it is these that will be reported on in detail in this report.

The profile sites were monitored from 19 December 2007 to 20 May 2008 on an approximately weekly basis by boat and involved the sampling of water in a 5 m integrated sample and a deep sample (approx. 0.5 m from the bottom). A Hydrolab sonde was also used to provide depth profiles at approximately 1 m intervals for water temperature, dissolved oxygen, electrical conductivity and pH. A secchi depth measurement was also taken. The integrated water sample samples were sent to AST laboratories for analysis of full algal counts, chlorophyll *a* and nutrients (dissolved [NOx, NH₄, FRP] and total [TN, TP]), while the deep sample was analysed only for nutrients (dissolved and total). The council sites were sampled with a single surface water sample and had algal cell counts undertaken.
In the second monitoring season (2008/09), monitoring was undertaken weekly (Table 1) from 4 November 2008 to 25 May 2009. The number of sampling sites for which nutrient and chlorophyll \( a \) were analysed was decreased. Vertical profile measurements with the Hydrolab were retained at all “Profile sites” (P1-P6), however nutrient analysis was only maintained at sites P1, P3 and P5, and chlorophyll \( a \) analysis was maintained at site P3. The sampling period was increased to November to May to ensure that the start of the bloom was detected.

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<tr>
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<td>Boat Ramp</td>
<td>Surface algal sample</td>
<td>Surface algal sample</td>
</tr>
<tr>
<td>C2</td>
<td>Blackstone</td>
<td>Surface algal sample</td>
<td>Surface algal sample</td>
</tr>
<tr>
<td>C3</td>
<td>Hadspron</td>
<td>Surface algal sample Discontinued after 3 weeks</td>
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<td>P1</td>
<td>Dam wall</td>
<td>Physico-chem profile Nutrients( ^{a} ) 5 m integrated algal sample Chlorophyll ( a )</td>
<td>Physico-chem profile Nutrients( ^{a} ) 5 m integrated algal sample</td>
</tr>
<tr>
<td>P2</td>
<td>North Basin</td>
<td>Physico-chem profile Nutrients( ^{a} ) 5 m integrated algal sample Chlorophyll ( a )</td>
<td>Physico-chem profile</td>
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<td>u/s Fire Logs Bay</td>
<td>Physico-chem profile Nutrients( ^{a} ) 5 m integrated algal sample Chlorophyll ( a )</td>
<td>Physico-chem profile Nutrients( ^{a} ) 5 m integrated algal sample Chlorophyll ( a )</td>
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<td>Opp. Honeymoon Bay</td>
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<td>Opp. Un-named creek</td>
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<td>Physico-chem profile Nutrients( ^{a} ) 5 m integrated algal sample</td>
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<tr>
<td>P6</td>
<td>Reedy Marsh</td>
<td>Physico-chem profile Nutrients( ^{a} ) 5 m integrated algal sample Chlorophyll ( a )</td>
<td>Physico-chem profile</td>
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\(^{a}\) Sampling included separate samples from 5 m integrated and deep water samples
Figure 3  Lake Trevallyn monitoring sites in 2007/08 and 2008/09
2.3 Hypotheses and analysis

The main hypotheses, based on preliminary analyses of data from the bloom in Lake Trevallyn in January – May 2007 and in December 2007 – May 2008 were:

- **Thermal stratification is necessary for the formation of a bloom in Lake Trevallyn.**

  This hypothesis was based on initial observations that the fluctuating size of the bloom tended to coincide with the presence or strength of thermal gradients in the upper part (approx. 5 m depth) of the water column. Strong thermal gradients are known to favour *Anabaena circinalis*. The buoyant cells of this species allow them to concentrate close to the surface when there is a low vertical mixing; a physical condition that is characteristic of thermal stratification. Under these conditions, *Anabaena circinalis* has the capacity to receive greater light than other non-buoyant species, increase their growth rate and therefore provide rapid increases in biomass (blooms).

- **Low flows through Lake Trevallyn are promoting the occurrence of blooms in Lake Trevallyn.**

  This hypothesis was based on observations that the summers of 2006/07 and 2007/08 both had lower flows from Poatina power station relative to previous summer periods (Figure 4). It appeared that the increased residence time provided greater time for *Anabaena circinalis* to grow and reach a biomass of significant proportions and/or that the lower flows may also have promoted thermal stratification.

- **The presence of available phosphorus is necessary for bloom development.**

  This hypothesis was based on initial observations in 2007/08 of high nutrient which may have promoted the development of a bloom. Phosphorus (P) was the most likely nutrient to be limiting to growth, and therefore likely to required before a bloom could develop. Sources of nutrients were not so clear (i.e. directly from inflows or from within the storage).

These hypotheses provide a very broad picture of the factors driving the blooms and provided a starting point from which to examine the data for 2007/08 and 2008/09 in more detail. The aim of this analysis was to examine patterns in the data and examine the potential hypotheses that could explain these blooms in 2007/08 and 2008/09. Final refinement of our knowledge of the blooms is provided.
3. Data analysis

3.1 Characterisation of blooms in 2007/08 and 2008/09

The blooms of 2007/08 and 2008/09 were considerably different from each other. The bloom in 2007/08 was widespread and long-lasting and reached high cell concentrations, however the bloom in 2008/09 was short-lived and had significantly lower cell concentrations. Sites C1 and C2 had cell concentrations that were typically higher than the profile sites that are closest to them in both monitoring seasons. This is probably due to the concentration of positively buoyant *Anabaena* cells in surface scums on these downwind shoreline sites (Table 2). Overall however, C1 and C2 showed the same general spatial and temporal patterns to the profile sites with the density of *Anabaena* higher in 2007/08 than in 2008/09.
Table 2 Total *Anabaena* concentration (x 10^3 cells/ml) from December to April in 2007/08 and 2008/09

<table>
<thead>
<tr>
<th>Site</th>
<th>C1</th>
<th>C2</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
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<th>P6</th>
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<td>21</td>
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<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
<td>1.3</td>
<td>0.8</td>
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<td>Max.</td>
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<td>18.2</td>
<td>52.4</td>
<td>32.9</td>
<td>51.6</td>
<td>10.4</td>
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<tr>
<td>Mean</td>
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<td>3.2</td>
<td>17.1</td>
<td>3.4</td>
<td>12.7</td>
<td>2.3</td>
<td>12.8</td>
<td>8.5</td>
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A significant *Anabaena* population was present throughout the majority of the lake during 2007/08 with all profile sites, other than P6, having median cell densities of >4,000 cells/ml from December to April (Table 2, Figure 5, Figure 6). *Anabaena* were present at P1, P2 and P3 throughout 2007/08 (December to April) and were present 95% and 85% of the time at P4 and P5, respectively. In contrast *Anabaena* was only detected at P6 for 25% of the time.

In 2007/08 transitory peaks in *Anabaena* numbers of >15,000 cells/ml occurred at all sites, with this density first being exceeded at the P2 site in mid January 2008. By mid February, P1, P2 and P3 had exceeded 15,000 cells/ml and by mid March the concentration of *Anabaena* had exceeded 15,000 at all 6 profile sites. Highest peak cell concentrations were observed at P1 (51,600 cells/mL) and P2 (61,400 cells/ml). Conditions favorable for *Anabaena* growth were present throughout the lake a number of times during 2007/08 with weekly increases of a factor of 3-4 being regularly observed (Figure 6).

The 2008/09 bloom contrasted with the previous monitoring season. For the first four months of the monitoring program (November to February), *Anabaena* cell numbers were undetectable or below 200 cells/ml at the three sites monitored. Cell densities from March until the end of May 2009 were generally below 5,000 cells/ml with peak densities occurring in mid April. In contrast to 2007/08 maximum cell densities during 2008/09 were found at the upstream site (P5: 41,600 cells/ml) and lowest near the dam (P1: 10,400 cells/ml).

Distributions of cell densities from each site from December to April from both monitoring seasons are plotted as box plots in Figure 5. Median and 75th percentile *Anabaena* cell numbers had a tendency
to increase with distance downstream in both monitoring seasons. In 2007/08 the median cell number and 75\textsuperscript{th} percentile increased between P5 and P2 and only decreased slightly at P1. In 2009, although cell densities were considerably lower, there was a similar general pattern of increasing cell density with distance downstream in the median and the 75\textsuperscript{th} percentile, indicating that on most occasions cell numbers were greater downstream. The difference in 2008/09 was that peaks were greater at the upstream sites (Figure 6, Table 2). The patterns of cell distribution and density suggest that conditions are generally more conducive to growth of *Anabaena* in the downstream reaches of the lake, and/or that transport of actively growing cells downstream led to higher cell densities as water transits the system.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{Summary statistics of *Anabaena* spp. cell numbers at sites sampled for the December - April periods of 2007/08 and 2008/09. Middle bar = median, boxes = 25\textsuperscript{th}-75\textsuperscript{th} percentile range, whiskers = range of data without outliers, stars = outliers within the 2-3x the interquartile range, circles = outliers greater than 3x the interquartile range.}
\end{figure}

The greatest observed weekly increases in *Anabaena* cell density were close to a factor of ten (Figure 6). All six profile sites showed a similar upper limit in the relative increase of cell numbers which suggests that conditions conducive to *Anabaena* growth can occur in all parts of the lake. Estimating growth rates from cell densities acquired from a fixed position in a flow based system such as Lake Trevallyn is only indicative of absolute growth rates; however, the similar pattern across sites indicates that there may be an upper limit on growth of approximately one cell doubling per two days in the system. This is a very similar growth rate to that observed in previous field studies of *Anabaena circinalis* (Sherman *et al* 1998) and to those observed in cultures of *Anabaena* cultures recently isolated from Lake Trevallyn (Chris Bolch, pers. comm. Feb 2010), and indicates that *Anabaena* has the capacity to increase rapidly when conditions are suitable.

Chlorophyll *a* rarely dropped below 5 µg/l during both monitoring seasons, with the exception of P6, which was more likely to have chlorophyll *a* concentrations of 3-4 µg/l. Typically, there was a large
amount of variability in chlorophyll $a$ concentrations between sites in 2007/08 that was primarily driven by transient peak concentrations at some of the sites. In general chlorophyll $a$ concentrations were lowest in early February and showed a trend of increasing concentration from February to May in both monitoring seasons. Peak values in chlorophyll $a$ were sometimes, but not always, correlated with high *Anabaena* cell numbers, particularly in 2007/08. In both 2007/08 and 2008/09 relatively high chlorophyll $a$ concentrations (>10 $\mu$g/l) occurred in the month prior to the onset of high *Anabaena* numbers, indicating that other algal species were able to attain significant biomass either in conditions that did not favor *Anabaena* growth or through outcompeting *Anabaena* for available resources (light and nutrients).

![Diagram of chlorophyll and algal counts](image)

**Figure 6** *Anabaena* and chlorophyll $a$ concentrations for all sites sampled during the 2007/08 and 2008/09 monitoring seasons

### 3.2 Water temperature

Water temperature in 2007/08 and 2008/09 showed a similar seasonal pattern of change, with surface water temperatures peaking around mid-late summer at 22-24 °C and falling to 12-14 °C by May (Figure 7). The timing of the peak in water temperature differed between 2007/08 and 2008/09 by approximately one month; the peaks were in early January in 2008 compared to early February 2009. The strong seasonal trend in temperature is overlain by shorter, more rapid variation in temperature of
2-3 °C occurring over 2-3 week periods. Temperature stratification of the top 6 m of depth, seen as temperature difference of 0.1-0.4°C/m, was seen on occasions from November to May (Figure 8).

Patterns of change in both absolute temperature and relative strength of stratification over weeks to months show a large influence of local weather conditions. Short and long term trends in temperature show similar patterns of change across all sites and are driven by physical forcing related to seasonal and shorter term variation in air temperature. Mean minimal and maximal daily air temperature (over the comparable periods of December to April) were slightly warmer (0.3 and 0.5 °C higher respectively) in 2007/08 than 2008/09 (Table 3). Similarly, mean and maximum daily wind speeds were slightly lower in 2007-08 (0.4 and 0.6 m/s lower respectively).

<table>
<thead>
<tr>
<th>Year</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
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</thead>
<tbody>
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<td>14.4</td>
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<td>22.9</td>
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<tr>
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<td>11.6</td>
<td>39.0</td>
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<tr>
<td>2008/9</td>
<td>2.5</td>
<td>26.9</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Table 3 Air temperature and windspeed in Launceston (Ti-Tree Bend – Bureau of Meteorology site). Statistics for December to April for 2007/08 and 2008/09

The higher air temperatures and lower wind speeds in 2007/08 may have influenced the stronger and more persistent stratification during this period (Figure 9). Rises and falls in surface water temperature follow rises and falls in mean daily temperature over periods of weeks to months in both monitoring seasons but appear more highly correlated in 2007/08 (Figure 9). Strength of stratification did not show significant correlation to trends in air temperature at the scale of weeks; however, the lower resolution of the stratification data (weeks) compared to the significant changes in air temperature that can occur over several days may mask any relationship between these parameters.
Temperature stratification of $>0.1^\circ C/m$ in the first 9 m of water depth occurred at all sites during both monitoring seasons of the sampling program (Figure 8). Strongest temperature stratification was generally confined to the first 6m of depth, indicating a relatively shallow thermocline. Temperature stratification was strongest and most persistent at the P2, P3 and P4 sites, slightly less intense at P1 and P5, and relatively weak at P6.

In 2007/08, temperature stratification ($>0.1^\circ C/m$) was present throughout most of the sampling program at all sites other than P6 (Figure 8, Figure 10). Temperature stratification of the first 6m of water column occurred for $>75\%$ of the sampling events during 2007/08 at sites P2, P3 and P4. Weak stratification ($>0.05^\circ C/m$ over 6 m depth) occurred throughout 2007/08 at sites P3 and P4. Strength of stratification in the first 3 m of depth increased with distance down the lake during 2007/08. On average during 2007/08, P6 showed the least temperature difference over 3 m and P2 the largest, indicating a more stable surface layer with distance down the lake (Figure 8). Partial mixing events occurred in late January and early February 2008 that decreased the depth and strength of stratification at P1-P4, and fully mixed the water column at P5 and P6. Stratification weakened from April to May 2008 as water temperature declined in the lake. P1 had substantially lower strength of stratification than P2 in the first 3 m of depth during 2007/08. Greater surface mixing at P1 may be influenced by wind induced mixing due to a greater exposure to prevailing winds or currents generated by flow to the dam offtake.

In 2008/09, temperature stratification ($>0.1^\circ C/m$) was less pronounced; it persisted for less than five weeks at a time and was much weaker than in 2007/08 (Figure 8, Figure 10). Full mixing events occurred in 2008/09 within surface waters (up to 9 m) at all sites at least once every five weeks and commonly within a four week period. Temperature stratification in 2008/09 was more likely to occur within the first 3 m of depth, with temperature differences at deeper depths being much less pronounced in 2008/09 than 2007/08 (Figure 8, Figure 10).

These differences in thermal stratification between 2007/08 and 2008/09 provide some support for the hypothesis that stratification is a major driver of blooms of *Anabaena* in Lake Trevallyn. The very large blooms of 2007/08 occurred when there was very strong and persistent stratification, while much less pronounced or persistent stratification in 2008/09 coincided with the smaller and less persistent bloom.

The difference in the timing of temperature peaks may also have influenced the bloom. As cyanobacteria are more competitive at higher temperatures (Tilman *et al.* 1986; Coles and Jones 2000), it may have been possible that the earlier establishment of the bloom in 2007/08 was mediated by the higher temperatures ($>\text{ approx. } 20^\circ C$) being seen earlier in the season (early January).
Figure 7 Water temperature at various depths for all profile sites for the monitoring seasons in 2007/08 and 2008/09
Figure 8  Water temperature difference from the surface for the depths of 3m, 6m and 9m at each profile site for monitoring seasons in 2007/08 and 2008/09
Figure 9  Comparison of physical factors and their influence on water temperature and thermal stratification in 2007/08 and 2008/09. (A) Daily wind speed data (maximum gust, daily mean wind speed) expressed as a 7-day moving average, (B) Daily maximum and minimum air temperature expressed as a 7-day moving average (C) Water temperature data from 1 m depth at all sites (D) Difference in water temperature of 3m, 6m and 9m with the surface at site P3
3.3 River flow and water residence time

River flow and residence time data are presented in comparison with algal cell data and temperature difference from the surface for various water depths in Figure 11. Total inflow into the lake generally varied between 1-3 Mm$^3$/d during both sampling seasons. Inflow tended to be lowest from the start of March until the end of May in both monitoring seasons, but was more variable during 2008/09 than in 2007/08. Water from the Macquarie River (Macquarie @ Cressy Pumps gauging site) represented more that 80% of the inflow entering the lake from December 2007 until early April 2008 (typically up to 95% for most of this period) (Figure 12). In contrast, the Macquarie River contributed a much more variable amount of water to total flow during 2008/09. The majority of flow at the Macquarie River @ Cressy Pumps site comes from water sourced from the Poatina power station outputs and is broadly representative of summer flows from Great Lake that pass through Poatina power station.
Some peaks due to natural inflows within the Macquarie catchment also occurred, but these were small relative to the power station contribution.

Natural flows from the Meander, Macquarie and South Esk Rivers entered the lake as three events in 2007/8, the first in late December 2007 the second in mid February 2008 and the third in early April 2008. The three events lasted two to three weeks and the combined natural contribution of these three rivers increased to ~45% of total inflow during these times. For most of May 2008, each of the three rivers contributed similar amounts of flow to the lake (~0.3 Mm$^3$/d each).

During 2008/09, inflows from the Meander River were >0.2 Mm$^3$/d for the whole sampling period. Inflow from the South Esk River was more variable, contributing very little of total flow in January and February 2009 but increased to approximately one third of the inflow for the remainder of the monitoring period from March to the end of May 2009.

There does not appear to be a strong influence of rates of river inflow over the two monitoring seasons of sampling on the development or persistence of temperature stratification. Significant temperature stratification occurred throughout the 2007/08 sampling period when flow rates were relatively stable at 1-2 Mm$^3$/d$^1$. Temperature stratification appeared to decrease in depth but remained intact when flow rates increased from ~1.5 to 3 Mm$^3$/d in the first half of January 2008. The effect of inflows during the 2008/09 program is more difficult to identify as inflow was more variable and periods of steady inflow spanning a number of weeks were rare. Inflows remained relatively stable at approximately 1 Mm$^3$/d from early March to late April 2009: an almost complete mixing event occurred at sites P1 to P4 in the middle of this period that suggests that factors other than inflows (e.g. air temperature, wind) can remix already stratified waters.

Water residence time in the lake varied from around four days to greater than 16 days but was generally between 4 and 12 days in both monitoring seasons. Water residence time was significantly shorter (~4 to 5 days) in the periods before March in 2008 and before January in 2009. After these times, the residence time increased to 10 to 16 days (i.e. flow through Lake Trevallyn decreased) for most of the remainder of both monitoring seasons. Low water residence times (4-6 days) during February 2008 did not prevent the formation of a significant *Anabaena* bloom in the downstream portion of the lake (P1-P3); however, an increase in water residence time to 10-12 days during early May 2008 may have promoted the occurrence of high *Anabaena* cell densities at all sites (other than P6) during mid to late May 2008.

Relatively high water residence times (>10 days) were present in the lake during January 2009 at the same time as significant surface temperature stratification occurred; however, no *Anabaena* were detected at any of the sites during this period. However, very high water residence times (~15 days) in

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$^1$ 1 Mm$^3$/d $\cong$ 11 m$^3$/s
mid April 2009 coincided with the highest cell densities recorded at the P3 and P5 sites during the 2008-2009 program.

Overall it is unclear to what extent inflow (and hence water residence time) influences both the formation and persistence of stratification and the occurrence of *Anabaena* blooms. Anecdotal evidence from historically high summer flows (pre 2007) in conjunction with the absence of significant *Anabaena* blooms suggests that residence times of around three days (equating to high power station output of around 3.5-4.5 Mm$^3$/d) may provide conditions that are not conducive to *Anabaena* growth or dominance. However, the 2007/08 and 2008/09 data indicates that significant stratification and bloom development can occur when residence times are as low as 4-6 days (flow rates of up to 2.5 Mm$^3$/d), and that at these flows there is some evidence that development of *Anabaena* blooms may be inhibited in the upstream two thirds of the lake (P3 to P6).

From this analysis, it appears likely that higher flow rates may inhibit the development of *Anabaena* blooms by reducing the depth and persistence of temperature stratification (thus reducing access to light for *Anabaena*) in the upstream portion of the lake. Higher flow rates will also decrease the water residence time in the lake which may lead to loss of algal biomass through dilution. This provides some support for the hypothesis that low flows will favour stratification and promote blooms in Lake Trevallyn. However, the effect of near maximum power station outputs over summer has yet to be tested by this monitoring program and may have the influence of reducing persistence of temperature stratification at downstream sites. However, the effect on the occurrence of blooms is unknown and maintenance of flows of this magnitude throughout summer to reduce stratification would be impractical in terms of the management of hydro-electric water resources.
Figure 11 Temporal *Anabaena* (bg = blue-green) cell counts at all sites compared to flows from each of the contributing rivers (Macquarie, Meander and South Esk) and the average weekly residence time of Lake Trevallyn.

Figure 12 An estimate of the flow at Macquarie River at Cressy pumps as a percentage of total flows through Lake Trevallyn. This is a proxy measure of the relative influence of the power station releases over summer, as a large proportion of flows at this site are sourced from the Poatina power station releases.
3.4 Electrical conductivity as a tracer for flow and mixing

Electrical conductivity (EC) can be considered a reasonably conservative tracer of flow and mixing when source waters for a water body either change in their relative salt load or if variable sources have differing concentrations of dissolved solids. In the case of Lake Trevallyn, there are three river systems that contribute inflows and in one of these (Macquarie River @ Cressy pumps) flows are frequently dominated from source waters derived from Great Lake that has low conductivity (~20-30 µS/cm). At times when the Macquarie River is the major source (>80% of total inflow) the EC of the lake remains below 50 µS/cm and when it comprises >95% of the flow EC in the lake will fall below 25 µS/cm. Catchment derived inflows from the other two rivers have much higher EC and can raise the lake EC levels to >65 µS/cm on average and as high as 100 µS/cm at the most upstream site (P6).

Short term high inflows from the Meander and South Esk Rivers which occurred in late December 2007, mid February 2008 and early April 2008 led to patterns of change in EC across the lake that indicate different rates of mixing and transport of water through the lake (Figure 13). P6 generally shows the earliest response to catchment inflows with EC often rising substantially a week before other sites; P6 is also the first to show a reduction in EC as catchment flows decline., A clear pattern of higher and earlier peaks in EC with distance down the lake was apparent in surface waters when total flow was low in April 2008. This indicates that the system did not reach equilibrium until several weeks after catchment flows from the South Esk and Meander became the dominant sources of water to the lake. Similarly from late January to late February 2009, there is a pattern of response in surface waters to the increasing contribution of Great lake waters as a decrease in EC at P5, P3 and P1 in turn, and the opposite pattern as the influence of Great lake water diminished during March 2009. Rates of change in EC between these sites are consistent with the calculated water residence times of 12 to 16 days during this period.

A common feature of all three natural higher flow events from the Meander and South Esk Rivers in 2007/08 was the attainment of higher and faster changes in EC in bottom waters relative to surface waters. (Figure 13). This pattern indicates that during 2007/08 when thermal stratification was present throughout most of the lake, inflowing water may be subducted during transit through the lake. During the 2008/09 program, differences in EC between surface and bottom waters were fairly minor and indicated that inflowing waters were being relatively well mixed through the water column on the scale of days.

A potential consequence of the subduction of inflows as a result of stratification is that surface waters would have higher residence times relative to deeper inflowing waters. This could also be a compounding factor in the maintenance of high biomass, as this could increase the residence times of surface waters (containing Anabaena) relative to deeper waters, reducing the possible diluting effect of
the inflow. These data therefore indicate that the hydrodynamics of flow in Lake Trevallyn may be influenced by thermal stratification and provides some evidence of a mechanism that may allow *Anabaena* to maintain its dominance in Lake Trevallyn.

3.5 **pH**

Surface and bottom waters at each site in both monitoring seasons showed pH values stayed within the expected range for these waters (pH 6.5-7.5) (Figure 14). There is an underlying small seasonal trend in bottom waters leading to minimum values when water temperature peaked (January –February) suggesting an effect of respiratory activity, presumably from the sediment, on bottom waters. There were significant rises in pH in surface waters for up to a few weeks at a time when algal biomass peaked, indicating high levels of photosynthetic activity. Similarly a decrease in pH in bottom waters
in March 2008 was probably caused by the settling of algal material leading to increased respiratory activity in bottom waters or sediments.

Figure 14 Surface and deep pH relative to *Anabaena* concentration for all sites sampled during the 2007/08 and 2008/09 monitoring seasons

3.6 Soluble nutrients

The soluble nutrients PO$_4$ (phosphate) NH$_4$ (ammonia) and NOx (nitrate and nitrite combined) showed patterns in concentration during both monitoring seasons that indicate an interaction between biological drawdown or release and supply from catchment or internal sources within the lake (Figure 15).
Phosphate was close to the limit of detection (<2 µg/l) on most occasions over summer in both monitoring seasons. Exceptions to this in 2008/09 were the gradually increasing concentration from mid March to the end of May 2009. Exceptions to these generally low concentrations in 2007/08 were some transient peaks during of up to 22 µg/l with most of the samples showing values above the detection limit coming from the upstream sites (P6, P5 and P4). Very low concentrations of phosphate during summer in both 2007/8 and 2008/9 indicate that this nutrient is the one most likely to limit primary production in the lake. The generally low concentration of phosphate in the system during the summer months is also likely to lead to the rapid assimilation of any phosphate delivered by source water to the lake into the biological cycle.

This rapid assimilation of phosphorus is evident in phosphorus peaks in response to natural inflows. Peaks in concentration were generally only measured in 2007/08 at the upstream sites of P5 and P6. This suggests that inflows may have been delivering sufficient phosphorus to initiate and maintain the bloom, but were low or undetectable by the time they reached the downstream sites of Lake Trevallyn. Interestingly, the start of the 2007/08 bloom in late December and early January coincided with elevated phosphorus at the P6 upstream site, with all other sites indicating concentrations above the detection limit. It is possible that the coincidence of this source of phosphorus with very strong stratification in January was a significant influence on the bloom’s early development in 2007/08. Similar coincidence of conditions was not as obvious in 2008/09, however increases in inflows in the South Esk River from early March 2009 were coincident with detectable phosphorus (Figure 15) and the occurrence of relatively strong, but less persistent stratification.

Ammonia was detected at most sites during both monitoring seasons and was commonly above 5 µg/l and often >10 µg/l. There were some medium term (weekly) patterns of change in ammonia concentration which occurred across most sites and led to a general increase or decrease in concentration in surface waters of 10-20 µg/l. The most prominent of these occurred from late April until late May 2009 and may be associated with release of nutrients from a declining algal bloom that occurred just prior to this time. Similarly, a sustained increase in ammonia from mid March to mid April in 2008 could be associated with high algal biomass and longer residence times of water in the lake. In general, the concentrations of ammonia detected in the lake indicate that nitrogen is unlikely to be limiting for algal growth for most of the summer. This is highlighted by the fact that high ammonium concentrations remained detectable during periods of both high algal photosynthesis (as indicated by high pH) and high algal biomass. This indicates that it is either efficiently recycled within the water column and/or is being supplied from inflows and sediment sources for most of the monitoring season.
NOx showed very clear temporal patterns in concentration with low values (generally <10 µg/l but often undetectable) in February and March of both seasons and were generally high (>20 µg/l but often >40 µg/l) at other sampling times. There appears to be a correlation with catchment inflows and increased NOx concentrations during times other than the summer months with increased natural inflows from the South Esk, Macquarie and Meander Rivers leading to greater NOx concentrations within the lake. The lack of detectable rise in NOx concentrations during a significant inflow event from the South Esk River in mid February 2008 may be due to a reduction in concentration in the source water during the mid summer or to the rapid use of NOx by the high algal biomass present in the lake at this time.
Figure 15 Nutrient concentration (phosphate, ammonia, nitrate + nitrite) relative to *Anabaena* concentration for all sites sampled during the 2007/08 and 2008/09 monitoring seasons compared with inflows and *Anabaena* concentration..
4. **Conclusions**

4.1 **Bloom drivers identified from analysis – refined hypotheses**

The following points describe the main findings of the drivers of *Anabaena* dominance, as determined from analysis of the data from Lake Trevallyn collected during 2007/8 and 2008/09:

- The *Anabaena* population differed significantly between 2007/08 and 2008/09. The 2007/08 was a significant and persistent bloom, that maintained a high cell concentration for four months between January and April 2008. In contrast, the 2008/09 bloom was initiated significantly later in the season, in March 2009 was of shorter duration (declining in late April 2009 and was significantly smaller in magnitude;

- The common condition that was seen with the occurrence of *Anabaena* blooms in Lake Trevallyn in both monitoring seasons was the occurrence of stratification. This appears to be an essential driving factor in the development of blooms in Lake Trevallyn, and has commonly been seen to be associated with the occurrence of blooms elsewhere (Sherman *et al* 1998);

- The difference in timing of higher water temperatures between 2007/08 and 2008/09 may have influenced the capacity for *Anabaena* to grow quickly relative to other taxa (e.g. green algae, diatoms) early in the season to establish a bloom population. A possible higher growth rate, influenced by the higher temperature early in the season in 2007/08, may have been a factor in the early establishment of *Anabaena*. Similarly a possible lower growth rate early in 2008/09, influenced by the later incidence of high water temperatures, may have been a significant factor preventing the early dominance by *Anabaena*.

- There is some correlation with the strength and duration of stratification and the size of the bloom. Stronger and more persistent stratification in 2007/08 appears to have provided more favourable physical conditions for the growth of *Anabaena* in that monitoring season;

- The formation and strength of stratification in Lake Trevallyn appears to be primarily driven by air temperature. Higher maximum and minimum temperatures in 2007/08 appear to be associated with more stable stratification in that monitoring season. The influence of wind on destratification is less clear with the coarser resolution of the monitoring data. There is also some evidence that higher flows may also weaken stratification, but not eradicate it;

- Thermal stratification may provide conditions that further compound the dominance of *Anabaena* in Lake Trevallyn. There is evidence that inflows from contributing rivers flow
underneath the surface mixed layer when stratification is strong, having the effect of a higher residence time for the surface layer and reducing the diluting effect of inflowing water;

- The limiting nutrient for phytoplankton growth is likely to be phosphorus, as ample sources of nitrogen were available in both monitoring seasons in surface waters. Inflows are likely to deliver new sources of phosphorus, however detection of these is difficult, particularly in the downstream reaches of Lake Trevallyn and is indicative of the fast biological uptake; and

- A possible driver for the initiation of the bloom in 2007/08 was the coincidence of very strong stratification with the presence of detectable phosphorus concentrations (apparently sourced from inflows). In this instance there appears to have been the combination of favourable physical and chemical conditions that provided the inoculum source with the capacity to rapidly grow and dominate over other species. Furthermore, high water temperatures (> 20°C) in January 2008 may have provided a competitive advantage to Anabaena over other phytoplankton through the effect on increasing growth rate in this cyanobacterium. In contrast, in 2008/09, there was not the same coincidence of strong stratification or high water temperatures with detectable phosphorus early in the growing season. It appears that available phosphorus, stratification conditions and water temperatures in excess of 20°C in March 2009 coincide with the initiation of the bloom in 2008/09, and are possible drivers for this late bloom.

4.2 Inoculum sources – an unknown factor

The potential inoculum sources of Anabaena are from a small (often undetectable) population of cells that is capable of surviving through winter, in combination with cells originating from germinating resting cysts (akinetes) (Baker 1999).

The absence of detectable cells throughout most of the 2008/09 monitoring could be partially driven by the weaker stratification in 2008/09 combined with insufficient availability of phosphorus, providing unsuitable growth conditions for a small “over-wintering” inoculum of Anabaena. It is also possible that conditions were not conducive to the germination of resting cells (akinetes) in 2008/09 or the formation of a significant number of akinetes in the previous monitoring season (2007/08) to add to the inoculum in 2008/09. There are a number of factors known to influence both the formation of akinetes and their germination. Conditions that are thought to initiate germination of akinetes include increased light availability (either from increased solar radiation or increased water clarity) light spectral quality (Thompson et al 2009), release of nitrogen and/or phosphorus from the sediments, seasonal increases in water and sediment temperatures and intermittent oxygen depletion at the

From the known complexities of factors that could influence akinete formation and germination and available data, it is not possible to determine the impact of different inoculum sources on the initiation or maintenance of blooms in Lake Trevallyn. However, it remains a viable hypothesis that could explain differences observed between 2007/08 and 2008/09.

5. Recommendations

5.1 Weekly monitoring program

The current monitoring program has provided a significant source of data that has been of great importance in understanding the blooms and processes in Lake Trevallyn. It is recommended that the monitoring program be continued between December and April.

The reduction in monitoring sites from six to three for the analysis of nutrients and cyanobacteria has provided a significant saving in costs but has continued to provide sufficient data to make necessary interpretations. Some minor alterations on the sampling program undertaken in 2008/09 to the analysis are recommended as follows:

- No longer sample Total Phosphorus and Total Nitrogen, as these are unlikely to provide information that is relevant to bloom dynamics.

- Undertake a full algal count at P3, to help in understanding the possible succession of species and competitors to *Anabaena* present in the water column.

The recommended 2009/10 sampling program is presented in Table 4.
Table 4  Proposed monitoring program for 2009/10

<table>
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<th>Site</th>
<th>Location</th>
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</tr>
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<tbody>
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<td>Boat Ramp</td>
<td>• Surface cyanobacteria sample</td>
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<tr>
<td>C2</td>
<td>Blackstone</td>
<td>• Surface cyanobacteria sample</td>
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<td>P1</td>
<td>Dam wall</td>
<td>• Physico-chem profile</td>
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<td></td>
<td></td>
<td>• Dissolved nutrients (deep and shallow)</td>
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<tr>
<td></td>
<td></td>
<td>• 5 m integrated cyanobacteria sample</td>
</tr>
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<td>North Basin</td>
<td>Physico-chem profile</td>
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<td>P3</td>
<td>u/s Fire Logs Bay</td>
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<tr>
<td></td>
<td></td>
<td>• Chlorophyll a</td>
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<td>Opp. Honeymoon Bay</td>
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<td>P6</td>
<td>Reedy Marsh</td>
<td>• Physico-chem profile</td>
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</table>

5.2 Continuous water temperature-depth measurement

It is recommended that installation of “thermistor chains” providing continuous water temperature measurement at a number of depths throughout the water column would be useful in understanding the dynamics of stratification in Lake Trevallyn. Current weekly sampling is at a scale that, while very useful, provides a resolution that cannot fully identify the factors that influence stratification on a scale that will influence the growth of Anabaena. Changes in the thermal structure of the lake are likely to occur on scales of hours to days, and an understanding of how such changes occur will provide a stronger understanding of the influence of stratification on the occurrence of blooms in Lake Trevallyn. Installation of a thermistor chain at or in the vicinity of P3 would be ideal, as this site has greater tendency to stratify, however concerns with vandalism and/or navigation may require installation in a location such as within the exclusion zone of the Trevallyn Dam, in the vicinity of P1.

The simplest and least expensive method of obtaining this data is through the installation of small, self contained temperature loggers that log at fifteen minute to hourly intervals. These instruments have the capacity to log temperature for more than a year at a time, and must be downloaded to obtain the
data (either in the field or when removed from the field deployment). The requirements for installation and operation of a thermistor chain are:

- 6x HOBO temperature loggers at $200 ea. (deployed at approx 2m intervals) $1,200
- Software and data downloading devices $500

In addition a buoy, chain and anchoring device would be required to attach the loggers at the required depths and to maintain its position in the lake.

5.3 Analysis of 2009/10 data

Following the completion of the monitoring program in 2009/10, it is recommended that analysis of data be undertaken in a similar manner to that presented in this report. This will allow the opportunity to further test the hypotheses and see if they are supported by the most recent data.

5.4 Possible mitigation measures

Mitigation against the occurrence of thermal stratification may be possible through the installation of one of a number of mixing devices. It is recommended that further investigation into the costs and effectiveness of such devices be undertaken. Potential cost-benefit analysis of the benefits of installation of devices should be undertaken as part of this investigation, which would include costs directly associated with the bloom (e.g. costs of water treatment, monitoring, analysis) as well as the potential benefits mitigation may provide (e.g. greater accessibility of Lake Trevallyn for recreational purposes, reduced costs for treatment, reduced health risks).

Initial investigations have identified two companies that provide these services. The companies (SolarBee and WEARS) both provide mixing devices that use impellers to either move water downwards from the surface or bring it up from deeper water. The aim is to increase the depth of mixing by breaking down stratification. A deeper mixed water column is unlikely to provide conditions favourable to the growth of buoyant cyanobacteria such as Anabaena.

Below is a summary of the possible costs as provided by these companies for the elimination of stratification in Lake Trevallyn and some limited information on their products. It is recommended that case studies for each of these products be investigated, so that an informed decision as to the potential benefits can be determined.
Table 5  Brief comparison of destratification units from WEARS and SolarBee

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<td>USA</td>
</tr>
<tr>
<td><strong>Product</strong></td>
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<td>Impeller that moves water upwards</td>
</tr>
<tr>
<td><strong>Requirements</strong></td>
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<td>3 units for Lake Trevallyn</td>
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<td><strong>Volume displaced</strong></td>
<td>180 ML/min</td>
<td>114 ML/min (combined 3 units)</td>
</tr>
<tr>
<td><strong>Type of installation</strong></td>
<td>Mains or solar</td>
<td>Self-contained solar</td>
</tr>
<tr>
<td><strong>Approximate cost</strong></td>
<td>A$125,000 plus installation</td>
<td>US$80-150,000</td>
</tr>
</tbody>
</table>

6. References


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