Artificial mixing for destratification and control of cyanobacterial growth in reservoirs
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Artificial mixing for destratification and control of cyanobacterial growth in reservoirs
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FOREWORD

Research Report Title: Artificial Mixing for Destratification and Control of Cyanobacterial Growth in Reservoirs

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CRC for Water Quality and Treatment Project No. 1.0.0.2.5.1 – Destratification for control of phytoplankton
EXECUTIVE SUMMARY

Problem

Cyanobacteria and their excessive growth in reservoirs pose a major unresolved water quality problem for the water industry. The risk to water quality arises firstly from taste and odour compounds, which are problematic at low cell concentrations, and secondly from toxins which become problematic at a higher biomass.

Copper - based algicides can be effective in controlling cyanobacteria but there are undesirable side effects. Disruption of the cells releases the taste and odours compounds and toxins which makes removal during treatment more difficult and the broad ecological impact may reduce the opportunity for natural controls. There is an urgent need for environmentally acceptable control methods.

The primary aim of CRC for Water Quality and Treatment project 2.5.1 was to investigate control of cyanobacteria by creating mixing regimes that are unfavourable to cyanobacteria and which limit the release of nutrients from the sediments. The project evaluated a hybrid artificial mixing system, which included raft-mounted mechanical mixers and a bubble plume aerator as a means of controlling cyanobacteria and low dissolved oxygen levels in Myponga Reservoir, South Australia. A major component of the evaluation involved monitoring and understanding the behaviour of the reservoirs in terms of physical, chemical and biological processes and to demonstrate how monitoring data could be used to predict the onset of water quality hazards.

The initial part of the report highlights the importance of incorporating reservoirs in a risk-based framework to manage water quality in the supply system and also the need for a high level of knowledge and understanding of the system. This is demonstrated by a conceptual model that identifies the processes leading to problems associated with cyanobacteria, pathogens and soluble metals (Fe & Mn). In particular, the significance of hydrodynamic processes in governing water quality processes is highlighted. A basic overview of cyanobacterial ecology and role of artificial mixing as an in-reservoir management strategy is also described.

Approach

The strategy proposed in this study involved using the bubble plume aerator to break down the primary thermocline while the surface mixers will be directed at entraining the warm surface layer including cyanobacteria into the main circulation pattern of the reservoir. Two approaches were used to evaluate artificial mixing. The first approach involved a 3-year monitoring program involving online and field measurements of physical (temperature), chemical (dissolved oxygen, Fe, Mn, nutrients) and biological parameters (chlorophyll, algal composition) in Myponga Reservoir. The second approach involved field investigations into the flow field around a surface mixer and numerical modelling of artificial mixing and reservoir hydrodynamics. This approach allowed for rapid assessment of different management strategies such as mixer entrainment volumes or mixer versus aerator configurations.
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ABBREVIATIONS

NATA National Association of Testing Authorities
TP Total Phosphorus
ADV Acoustic Doppler Velocimeter
AHD Australian Height Datum
CAEDYM Computational Aquatic Ecosystem Dynamics Model
CCPs critical control points
Chl a Chlorophyll a concentration
DO Dissolved oxygen
DYRESM Dynamic Reservoir Simulation Model
FRP Filterable reactive phosphorus
GAC Granular activated carbon
NHMRC National Health and Medical Research Council
NOx Nitrate (NO2) + Nitrate (NO3)
PAC Powdered activated carbon
PAR Photosynthetically-active radiation
SML Surface mixed layer
TKN total Kjeldahl nitrogen
WHO World Health Organisation
1 INTRODUCTION

1.1 Aims

The primary aim of this project was to evaluate a destratification technique, involving raft-mounted mechanical mixers deployed at the surface and directed downwards, to mix the water column as a means of controlling the abundance of cyanobacteria in reservoirs. An additional aim included comparing surface mechanical mixing to bubble-plume aeration in destratifying the water column, improving Dissolved Oxygen levels and reducing cyanobacteria. A major component of the evaluation was the monitoring and understanding of the behaviour of the reservoir in terms of physical, chemical and biological processes. The second aim of the project was to demonstrate how monitoring data could be used to predict the onset and abundance of cyanobacteria and to evaluate management strategies including bubble-plume aeration.

1.2 Background

Cyanobacteria and their excessive growth in reservoirs pose a major unresolved water quality problem for the water industry. The risk to water quality arises firstly from taste and odour compounds, which are problematic at low cell concentrations (Bowmer et al. 1992) and secondly from toxins which become problematic at a higher biomass (Chorus and Bartram, 1999). Concern about the health risks from cyanobacterial toxins has focussed attention on guidelines for drinking water supplies. A guideline was formulated by WHO for a variant of the microcystin toxin and a modification of that guideline is in use in Australia. Guidelines are also being considered for other toxins such as saxitoxin and cylindrospermopsin but there are currently insufficient toxicological data available to recommend them at present.

Toxins can be removed by treatment but not without difficulty and considerable expense. Some toxins can be oxidised with chlorine provided contact times are sufficient. Powdered activated carbon (PAC) is effective but incurs significant cost, as high dose rates may be required for indeterminate periods depending upon the intensity and duration of the bloom. Granular activated carbon (GAC) and advanced oxidation (ozonation) are also effective but are not commonplace in conventional treatment plants. The taste and odour compounds are more difficult to remove as they are not affected by chlorine.

Against this background of heightened need for control, and the relative expense of water treatment plant solutions, there is a range of control strategies for cyanobacteria in source water. These are not mutually exclusive from water treatment and need to be assessed as part of a multiple barrier for their utility in terms of suitability for local circumstance, timescale of effect and cost. In addition to catchment strategies to reduce eutrophication, the in-reservoir techniques include nutrient reduction by chemical flocculation and precipitation, algicides and artificial mixing for destratification to reduce growth of cyanobacteria. Artificial destratification is a potentially cheaper option in contrast to sole reliance on water treatment options. However, mixing techniques have a long history of use with variable success. In this report we highlight the need to understand storage behaviour and the processes, which generate hazards such as cyanobacteria. Such an integrated approach requires historical data analysis and effective water quality monitoring. In light of this data, the potential of techniques such as artificial mixing can be evaluated with more confidence.

1.3 Reservoir management

There is a widespread trend in the Australian water industry to adopt a risk-based approach to the management of water quality. The intention of frameworks such as the NHMRC “Framework for Management of Drinking Water Quality” (McRae et al., 2001) is to shift the focus of water quality management away from “end product testing” or compliance monitoring to overall quality assurance management of the system. The framework approach embraces the span of catchment to tap and requires system knowledge and understanding. It also incorporates the principles of both multiple barriers for hazard interception and management and “critical control points” (CCP’s) to enhance security in the supply system. The critical control points by definition require both continuous monitoring and are also process steps that are amenable to intervention or corrective action to prevent
a downstream problem. The aim is to control hazards as close as possible to their source (Deere and Davison, 1998). In the case of a reservoir as a component of the water supply system, a potential CCP is the offtake, where intervention could consist of selection of different depths to take water or the turning on of a destratification unit as the water column becomes stratified.

1.4 Reservoir processes, hydrodynamics and time-scales of hazard development

An essential component of a risk-based management framework for water quality is the requirement for a high level of knowledge and understanding of the system in question. To develop this requires the assessment of historical information to identify hazards and to understand how they could evolve into risks in that system. In reservoirs, it is important to understand both the processes that control the hazards and the time-scales over which they occur. A conceptual model that incorporates the process understanding of how cyanobacteria, pathogens and soluble metals (Fe & Mn) develop in a reservoir is given in Figure 1. Cyanobacterial growth occurs within the surface layers and consequently is strongly influenced by changes in depth of the Surface Mixed Layer (SML) and meteorological conditions, which can change on a scale of minutes to days.

The dynamic nature of the above water quality processes is overlain by the hydrodynamic processes operating in the reservoir. That is, the dynamic heating and cooling of the water, which is influenced by solar radiation, wind speed and direction and inflow events. The most recognised hydrodynamic process in reservoirs which affects most chemical and biological processes is thermal stratification, where reservoirs are divided into discrete layers separated by sharp gradients in density (Figure 2). The scale of change for density layer formation, internal wave generation and vertical and lateral transport is rapid (Imberger, 1999) and variable and these processes drive the chemical processes on similar short-term scales.
Figure 1 Conceptual model of factors contributing to the evolution cyanobacterial, metal or pathogen hazards in reservoirs.
1.5 Cyanobacteria

There are three pre-requisites for cyanobacterial growth: adequate light, adequate nutrient supply and an inoculum from which the population can propagate. A key characteristic of cyanobacteria is their buoyancy, which enables them to float during periods of low turbulence when other species tend to sink below the diurnal thermocline. The depth of the diurnal thermocline changes in response to wind mixing and air temperature and consequently on warm, calm nights a shallow thermocline persists. As the thermocline deepens the phytoplankton are mixed deeper and spend more time out of the euphotic zone and may become light limited. In deep, well-mixed reservoirs, cyanobacterial numbers are generally suppressed relative to other taxonomic groups, namely diatoms and green algae. Seasonal succession follows the general pattern: green algae → diatoms → dinoflagellates → cyanobacteria, as a function of increasing water stability (Round, 1971). Species such as *Microcystis aeruginosa* and *Anabaena circinalis* have maximal growth rates when they experience a daily light dose of photosynthetically active radiation (PAR: 400–700 nm) of approximately 7 mol photons m⁻² d⁻¹ (Reynolds, 1997). This occurs when the diurnal thermocline is approximately the same depth as the euphotic depth.

Once suitable physical conditions are established, the growth will depend on the presence of an inoculum and the nutrient supply. These factors can be determined in a routine monitoring program whereas the dynamic physical environment of stratification and mixing can be best assessed by online temperature profiling. Although cyanobacteria are often perceived as a symptom of eutrophication, the paradox is that they do not require high concentrations of nutrients to reach relatively high biomass. Concentrations of phosphorus less than 0.01 mg L⁻¹ filterable reactive phosphorus (FRP) are considered to be growth limiting (Sas, 1989) and 0.1 mg L⁻¹ soluble inorganic nitrogen is considered the minimum concentration to maintain growth during the growing season (Reynolds, 1992). Higher concentrations support rapid growth.

1.6 Artificial mixing

Artificial mixing has been widely applied to control oxygen deficiency and nuisance phytoplankton in lakes and reservoirs (e.g. Steinberg, 1983, Jungo *et al.*, 2001, Daldorph, 1998, Simmons, 1998). The relative success of mixing devices will depend on numerous factors such as the bathymetry and size of the storage in question, aerator design, problematic algal species and nutrient status of the storage. The most frequently used mixing devices are bubble plume aerators (Figure 3). Bubble plume aerators are located near the bottom of the water body and operate by entraining water with fine air bubbles, which mixes and propagates an intrusion generating circulation and increasing the exchange of water.
between the deep and shallow layers. The increased circulation reduces differences in temperature, oxygen and nutrients between the epilimnion and hypolimnion.

During periods of hot calm weather, aerators may not prevent the development of thermal structure in the surface waters. Monitoring of Myponga and Little Para Reservoirs in South Australia has shown that periods of surface heating have been associated with blooms of toxic *Anabaena circinalis* (SA Water, unpublished). Similar patterns have been observed in Chaffey Dam-NSW (Sherman, pers. comm.). The small temperature gradients that previously would not have been considered ecologically significant may provide sufficient stability to allow cyanobacteria to become dominant. The challenge is to find practical ways of preventing the establishment of a buoyant surface layer.

Mechanical mixers, in the form of impellers directed vertically have been used as an alternative method of destratifying reservoirs. Mechanical surface mixers operate by means of a large impeller mounted on a raft in the reservoir (Figure 3). Rotation of the impeller draws water from the surface layer and transports it through a large column (draft tube) to the desired depth. Water movement due to the impeller increases kinetic energy within the system and creates thermal instability. The motivation behind using this type of destratification technique is to decrease the residence time of water in the illuminated surface layer. The aim is to circulate the cyanobacteria, from the surface layer, through the water column into deeper and darker water thereby inducing light limitation.

![Figure 3](image)

**Figure 3** Flow field around a bubble plume aerator (a) and surface mechanical mixer (b).
1.7 Approach and Myponga Reservoir

The CRC for Water Quality and Treatment in collaboration with the South Australian Water Corporation (Bulk Water Division) undertook a detailed scientific study to evaluate the performance of surface-mounted mixing and bubble plume aeration systems. The study involved the installation of two surface mixers in addition to an existing bubble plume aerator in Myponga Reservoir. Myponga Reservoir was chosen as a field site because it experiences cyanobacterial blooms consisting of *Anabaena circinalis*. Copper sulphate is used as an algicide at this reservoir and mechanical mixers were installed previously between 1989-1990. Three Flygt mixers capable of moving 3000 L s⁻¹ were attached to the dam wall and set at an angle to entrain hypolimnetic water from below the thermocline into the surface waters. While this arrangement was partially successful in creating localised isothermal conditions, the reservoir still required treatment with copper sulphate once or twice per year to control *Anabaena* blooms. It appears that when mixers are used to entrain water from below the thermocline the same surface heating issues as described for the aerators can also arise.

The strategy proposed in this study was to evaluate the performance of a hybrid mixing system by combining bubble aerators with surface mechanical mixers. The intention was that the aerator was used to break down the primary thermocline while the mixers were directed at entraining the warm surface layer into the main circulation pattern of the reservoir. To date there has been no tool available to determine whether the use of surface mixers will result in improved water quality.

Two approaches were used in this study to evaluate artificial mixing. The first approach involved monitoring physical, chemical and biological parameters of the storage. In particular, determine the processes, which favour the development of *Anabaena*. The second approach involved field investigations into characterising the flow field around a mixer and the use of numerical modelling to determine the affects on hydrodynamics and potential *Anabaena* growth. This approach allowed for rapid assessment of different management strategies such as mixer entrainment volumes or mixers versus aerator configurations.

The key objectives of the study were:

1. Establishment of a monitoring program to understand the behaviour of the storage.
   - To determine the seasonal changes in phytoplankton species in Myponga Reservoir
   - To determine the relationship between nutrients and phytoplankton
   - To determine the nutrient loading and relationship with rainfall

2. Interpretation of monitoring data to understand cyanobacterial development.
   - To determine the factors contributing to growth of *Anabaena circinalis*.
   - To predict growth of *Anabaena circinalis* using physical and nutrient data.

3. Assessment of historical data to evaluate bubble plume aeration.

4. Characterisation of the flow field of the surface mechanical mixers.

5. Develop a surface mechanical mixer algorithm to be incorporated into DYRESM.

6. Application of hydrodynamic–ecological models (DYRESM-CAEDYM) to characterise reservoir hydrodynamics and the influence of surface mixers and the bubble plume aerator on stratification, oxygen levels and phytoplankton (cyanobacteria, green algae).

7. Simulate a range of artificial mixing strategies and evaluate their impact on cyanobacteria
   - No artificial intervention
   - Aerator and surface mixers with no CuSO₄ dosing
   - Aerator only
   - Surface Mixers at measured flow rate (3.5 m³ s⁻¹)
   - Surface mixers at design flow rate (5 m³ s⁻¹)
   - Surface mixers at increased flow rate (8 m³ s⁻¹)
   - Intermittent operation
   - Equivalent aerator energy input using surface mixers
2 MATERIALS AND METHODS

2.1 Myponga Reservoir site description

Myponga Reservoir (S 35° 21' 14", E 138° 25' 49") is a drinking water reservoir located on the Fleurieu Peninsula, 70 km south of Adelaide in South Australia (Figure 4). The reservoir has a capacity of 26,800 ML at a full supply level of 211.7 m A.H.D (Australian Height Datum), an average depth of 15 m, a maximum depth of 36 m and a surface area of 2.8 km². The mean retention time based on abstraction is approximately 3 years. Water is removed from the reservoir via an off take valve located on the dam wall at 195.2 m AHD. The majority of the catchment is drained by Myponga River, which feeds the ‘long-arm’ of the reservoir on the eastern side (Figure 4). The entire catchment is approximately 124 km² of mixed land use, including improved pasture for dairy, beef and hay production, with patchy remnant native vegetation. Recent estimates of dominant land uses are 62 % grazing and 24 % dairying (Thomas et al., 1999). The location of the two surface mixers, bubble plume aerator and two meteorological (MET1 and MET2) stations incorporating thermistor chains are shown in Figure 5.

Figure 4 Location and map of Myponga Reservoir showing the positions of the meteorological stations incorporating thermistor chains, surface mixers and aerator near dam wall (offtake).
2.2 Understanding the behaviour of Myponga Reservoir: monitoring program

To evaluate the impact of artificial mixing and to determine which other processes influence water quality in Myponga Reservoir a detailed limnological monitoring program was undertaken between 1998 and 2001. The monitoring program included measurements of physical, chemical and biological parameters. Physical data from the meteorological stations was downloaded via telemetry at the Australian Water Quality Centre and analysed using Magpie software (MEA Australia). The temperature data was used to model the hydrodynamics of Myponga Reservoir with DYRESM. Inflows from Myponga River were also monitored at a gauging station approximately 5 km upstream of the reservoir. At the station, a bubble plume gauge height flow rated logger submersed at a V-notch weir provided flow measurements and an accumulated flow-triggered auto-sampler (ISCO, Model 3700), Nebraska USA) enabled samples to be taken from the hydrograph. Sample flow at the gauging station was monitored using telemetry.

2.2.1 Routine sampling program

The routine sampling program consisted of sampling for nutrients and phytoplankton to determine the nutrient loading into the reservoir and to assess if there were any patterns in nutrient limitation or phytoplankton succession. Samples for nutrients were collected weekly from Location 4 at the surface, 10 m, 20 m and 30 m and from Myponga River. Additional samples were collected once a month from Location 7 (surface, 5 m, 10 m, and 15 m) to determine if there were any differences between the main basin and long sidearm. For brevity we report only on results from Location 4. All nutrient analyses including filterable reactive phosphorus (FRP), total phosphorus (TP), ammonia (NH₄), nitrate and nitrite (NOₓ) and total Kjeldahl nitrogen (TKN) were carried out by the Australian Water Quality Centre (ISO 9001) NATA Accreditation No. 1115; Chemical testing).

Weekly samples were collected for identification and abundance of phytoplankton from Locations 1, 4, 5, 6 and 7 which have the prefix 122 in the map below (Figure 5). The site for sampling Myponga River is 1655. All reservoir samples were taken from the surface to 5 m depth using a hosepipe. Table 1 summarises the sampling program and associated instrumentation used at Myponga Reservoir.

![Sampling locations in Myponga Reservoir](image)

**Figure 5** Sampling locations in Myponga Reservoir.
Table 1 Sampling program and associated instrumentation used at Myponga Reservoir

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensor/Sample type</th>
<th>Depth (m)</th>
<th>Frequency</th>
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<tbody>
<tr>
<td><strong>Meteorological station</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water temperature</td>
<td>Betatherm thermistor</td>
<td>15 depths through water column</td>
<td>10 min</td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>Climatronics WM-111</td>
<td>2 m above water</td>
<td>10 min</td>
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<tr>
<td>Air temp and relative humidity</td>
<td>Vaisala Oyj Model HMP-45A</td>
<td>Mounted on raft</td>
<td>10 min</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Middleton EP09 v1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shortwave (300-3000 nm)</td>
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</tr>
<tr>
<td>Upwelling and downwelling Longwave (0.3-60 µm)</td>
<td>Middleton CN1-R v1.2.3</td>
<td>Mounted on raft</td>
<td>10 min</td>
</tr>
<tr>
<td>Redox potential</td>
<td>Greenspan</td>
<td>30 m depth</td>
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<td><strong>Reservoir water column</strong></td>
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<tr>
<td>Chlorophyll a</td>
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<td>1, 4, 5, 6, 7</td>
<td>Weekly</td>
</tr>
<tr>
<td>Phytoplankton abundance</td>
<td>5 m-integrated</td>
<td>1, 4, 5, 6, 7</td>
<td>Weekly</td>
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<tr>
<td><strong>Nutrient monitoring</strong></td>
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<td></td>
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<tr>
<td>TN, TP, FRP, NO₃, NH₄</td>
<td>4 depths</td>
<td>4</td>
<td>Weekly</td>
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<td><strong>Myponga River</strong></td>
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<td></td>
<td></td>
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<tr>
<td><strong>Stream inflow</strong></td>
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<td></td>
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<tr>
<td>TN, TP, FRP, NO₃, NH₄</td>
<td>Weekly and event sampling</td>
<td>Myponga Creek</td>
<td>Event dependent</td>
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<td>Flow</td>
<td>Gas bubbler at V-notch weir</td>
<td>Myponga Creek</td>
<td>15 min</td>
</tr>
<tr>
<td>Temperature</td>
<td>Betatherm thermistor</td>
<td>Myponga Creek</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Using physical data to determine cyanobacterial growth in Myponga Reservoir

A key aim of this project was to evaluate whether the artificial destratification systems are able to limit the growth of *Anabaena circinalis*. The continued use of copper sulphate as an algicide limited the opportunities for this to be examined in the field. An alternative approach is to determine what physical conditions favour *Anabaena* and evaluate whether these persist for sufficient time in Myponga Reservoir for a large *Anabaena* population to develop.

The euphotic depth and mixed depth were examined and a simple model was used to determine the average light dose that would be received if a cyanobacterial cell was travelling through a particular mixed depth. A light dose/growth curve of *Anabaena circinalis* was developed and used to assess the duration of conditions suitable for high growth in Myponga Reservoir.

2.4 Assessment of bubble plume aeration: evidence of improved water quality

To investigate how effectively the bubble plume aerator in Myponga Reservoir oxygenated the hypolimnion and controlled the resolubilisation of iron and manganese a review of historical and monitoring data was undertaken. The key parameters investigated included: DO, iron and manganese concentrations and the degree of stratification as determined from temperature measurements. Water temperature was measured weekly at a location near the dam wall adjacent to the offtake site (Figure 4). Temperature and DO were measured at the surface, 10 m, 20 m and 30 m using a Yellow Springs Instruments probe. Iron and manganese concentrations were determined from monthly samples collected at the surface and 30 m from the same location. The sampling location is approximately
20 m from the aerator line which, when operational induces considerable mixing. The monitoring was undertaken by Bulk Water Division, SA Water and chemical determinations performed at the Australian Water Quality Centre, Bolivar South Australia.

2.5 Evaluation of surface mechanical mixers

2.5.1 Surface mixer description

Two raft-mounted surface mixers were installed in Myponga Reservoir in 1999 (Figure 4). (Hereafter referred to as the 800 m and 400 m mixers, related to their installation distance relative to the dam wall.) The surface mixers are driven by 4 kW motors pumping the top 1-2 m of surface water, down through a draft tube (diameter 4.9 m, length 13 m), employing an 8-blade impeller with a diameter of 4.9 m (Figure 6). The blades have a fixed pitch angle of 15° and the impeller rotates at 10 rpm.

![Figure 6 Schematic diagram of the surface mixers, arrows indicate the direction of flow.](image)

2.5.2 Field investigation: flow measurements

Extensive flow measurements were made around the 800 m surface mixer to gain an understanding of the volume of water entrained by the mixer, the flow field exiting the draft tube and the influence of both stratification and isothermal conditions on performance. In addition, a surface mixer algorithm was developed for the hydrodynamic model DYRESM applied to Myponga Reservoir to simulate the flow and velocity measurements below the draft tube.

A field version Acoustic Doppler Velocimeter (ADV) with internal electronic compass and thermistor was suspended from a fixed mooring adjacent to the 800 m surface mixer to measure the flow field.

Velocity measurements were recorded at 50 Hz for 2-minute intervals at 500 mm depths through the water column. The process was repeated at numerous distances from the surface mixer ranging from 1-500 m. The measurements were time-averaged using the 2-minute sampling time to ensure that the required velocity fluctuations were resolved. At the exit of the draft tube radial, tangential and vertical flow was detected.

To determine the penetration depth of the exiting flow a propeller meter was vertically mounted on a bracket and lowered underneath the draft tube. Measurements were recorded across the diameter of the draft tube at 0.3 m intervals. The measurements were carried out on the 26/9/2000 when a 4°C temperature difference existed between the surface and reservoir bottom.
2.5.3 Description of hydrodynamic-ecological models: DYRESM & CAEDYM

DYRESM (Dynamic REServoir Simulation Model) and CAEDYM (Computational Aquatic Ecosystem Dynamics Model) were developed by the Centre for Water Research, University of Western Australia. DYRESM is a one-dimensional hydrodynamic model for predicting the vertical distribution of temperature, salinity and density in lakes and reservoirs. While CAEDYM is a complex ecological model which can simulate primary production, secondary production, nutrient and metal cycling, and oxygen dynamics. DYRESM assumes that water bodies comply with the one-dimensional approximation in that the destabilising forcing variables (wind, surface cooling, and plunging inflows) do not act over prolonged periods of time and the model provides a means of predicting seasonal and inter-annual variation in lakes and reservoirs as well as sensitivity testing to long-term changes in environmental factors or watershed properties. Prior to this study, DYRESM could only cater for artificial destratification involving bubble plume aerators and did not possess an algorithm for surface mechanical mixers. DYRESM can be run either in isolation, for hydrodynamic studies or coupled to CAEDYM (Computational Aquatic Ecosystem Dynamics Model) for investigations involving biological and chemical processes. Both models are available as freeware from the internet (http://www.cwr.uwa.edu.au/services/models.php)

2.5.4 Development of surface mixer algorithm

The algorithm representing the behaviour of the surface mixers was incorporated into the one-dimensional model DYRESM. The algorithm is based on a simple buoyant plane plume, with the plume geometry corresponding to the base of the draft tube, i.e. \( \pi D \) where \( D \) is the diameter of the draft tube. The surface mixer draws water from the top 1-2 m of the water body, which emerges as a radial plume at the base of the draft tube. The density of the inflow to the surface mixer is assumed to be less than or equal to the ambient water at the exit of the draft tube. As the plume rises through the water column it entrains water from the surrounding environment, thus increasing the density of the plume. As the density increases the plume velocity decreases until the point of neutral buoyancy is reached where horizontal insertion occurs.

The buoyancy flux (L$^3$T$^{-3}$) of the plume is defined by:

\[
B = g \left( \frac{\Delta \rho_v}{\rho} \right) Q_p (\pi D)^{-1}
\]  (1)

in which \( \Delta \rho_v \) is the density difference between the surrounding fluid and the discharged fluid, and \( D \) is the diameter of the draft tube. The plane plume equation for the volume flux, \( Q_p \) (L$^3$T$^{-1}$), used is based predominantly on the comprehensive experimental investigation of Kotsovinos and List (1977) and is given by:

\[
Q_p = 3.32 \left( \frac{\rho}{2} \right) \frac{1}{\sqrt{B}} (\pi D)
\]  (2)

where \( z \) is the depth and \( \alpha \) is the entrainment coefficient (0.083) for plane plumes (Fischer et al., 1979) and is divided by 2 as entrainment will not occur on the inside of the plume due to it rising against the external wall of the draft tube. The coefficient in equation 2 implies that 35% of the flux is turbulent transport while 65% is due to the mean flow (Fischer et al., 1979).

The algorithm assumed the following:
- No initial momentum exists in the surface water entering the surface mixer.
- The available impeller energy is always able to pump the surface water down to the outlet of the draft tube.
- The flow exiting the draft tube has no jet characteristics
- The attributes of the internal draft tube flow are the same as the surface water.
2.6 Simulating the operation of the aerator and surface mixers in Myponga Reservoir

Validation of the surface mixer algorithm and the use of the existing DYRESM aerator algorithm enabled the impact of artificial mixing upon cyanobacterial growth and dissolved oxygen (DO) to be investigated. To obtain realistic results, the model simulation needed to include competition for resources from other phytoplankton groups. The growth of three phytoplankton groups, Chlorophyceae (Scenedesmus sp.), Bacillariophyceae (Nitzschia sp.), Cyanophyceae (Anabaena circinalis) were simulated with the DYRESM-CAEDYM coupled hydrodynamic and ecological process model. In addition, CAEDYM was used to model DO dynamics and the surface mixers were simulated for their ability to maintain levels above 4 to 5 mg L\(^{-1}\) in the entire water column. The DYRESM-CAEDYM simulation of phytoplankton growth and DO dynamics was validated against field data measured in Myponga Reservoir between 1-September-1999 and 1-September-2000.

The phytoplankton growth parameters used in the CAEDYM model are unique to each phytoplankton group and are dependent upon environmental conditions (e.g. nutrient concentrations, light environment and temperature). An extensive literature search was undertaken to determine the appropriate growth parameters required for light and nutrient limited growth for Scenedesmus sp., Nitzschiia sp. and Anabaena circinalis (summarised in table 1, Appendix I). The parameters were used in the CAEDYM growth functions as described in Lewis (2003).

2.6.1 CAEDYM Code: New CuSO4 dosing algorithm

To satisfactorily simulate the phytoplankton assemblage at Myponga Reservoir the inclusion of CuSO\(_4\) dosing algorithm was required on 11 and 12 January 2000. The CuSO\(_4\) algorithm incorporated into CAEDYM reduced the total phytoplankton biomass in the water body over a period of two days. The simulated reduction of phytoplankton biomass was achieved by adding an extra function in the phytoplankton respiration subroutine in CAEDYM (Equation 8.1) that was linked to the respiration rate (Equation 76) as described in Lewis (2003).

2.6.2 Model validation

To undertake calibration and validation of the CAEDYM simulation the appropriate state variables were defined. The state variables are quantities that vary with time and are used to characterise the state of the reservoir at any time (Riley and Stefan, 1987). In the CAEDYM model set-up for Myponga Reservoir the state variables were biomass as Chl \(\alpha\) concentration (µg Chl \(\alpha\) L\(^{-1}\)) for greens, cyanobacteria and diatoms; DO, temperature, phosphorus, nitrogen and silicon concentrations.

Myponga Reservoir field data demonstrated that nutrient concentrations are sufficient for growth for relatively long periods but that significant phytoplankton growth only occurs when the light and temperature conditions are favourable. The calibration of the simulated phytoplankton growth in Myponga Reservoir was restricted to the maximum potential growth rate of phytoplankton \(\mu_{\text{max}}\), the parameter for initial slope of each group’s photosynthesis versus irradiance curve \(I_{\text{a}}\), respiration rate \(kr\), settling velocity \(z_s\), and the half saturation rates for nutrient uptake \(K_P\), \(K_N\) and \(K_Si\) (Appendix I). These parameters were calibrated by trial-and-error adjustment for each phytoplankton group. The objective of this process was to maximise the correlation between the observed and simulated total and individual Chl \(\alpha\) concentrations for the entire modelled period whilst maintaining the parameters within 10% of their published values, thus maintaining the integrity of the physiological constants. During the calibration one parameter was adjusted at a time. The parameter values that gave the best correlation between the simulated and field data during the period September-1999 to September-2000 are shown in Appendix I).

The validation of the DYRESM-CAEDYM simulation was based on data collected for the period September 1999 to August 2000 including thermal structure (obtained from meteorological data), DO concentration (mg L\(^{-1}\)) and phytoplankton growth (as total Chl \(\alpha\), µg Chl \(\alpha\) L\(^{-1}\)).
3 RESULTS AND DISCUSSION

3.1 Behaviour of Myponga Reservoir: monitoring results

3.1.1 Nutrients and chlorophyll

Phosphorus is often considered to be the element which limits the maximum yield of the phytoplankton biomass. In deep lakes or reservoirs phosphorus is either incorporated into phytoplankton biomass, lost from the system via outflow or buried in the sediment as particles sink. Phosphorus/ nitrogen and chlorophyll concentrations are shown in Figure 7 and Figure 8, respectively. Monitoring showed that generally filterable reactive phosphorus (FRP) and soluble inorganic nitrogen (NO₃) concentrations were homogeneous throughout the water-column and therefore the surface concentrations represent the entire water-column. Nutrient concentrations within the reservoir reflected catchment loading associated with rainfall and algal growth during spring and summer. A comparison between nutrient and chlorophyll concentrations for Location 4 generally shows that FRP and NO₃ concentrations are high in winter and spring but decrease with algal growth in summer. The highest FRP and NO₃ concentrations were recorded through winter and spring. FRP reached maximum concentrations of 0.041 mg L⁻¹ in September 1999 and 0.08 mg L⁻¹ in November 2000. Maximum NO₃ concentrations of 0.69 mg L⁻¹ and 0.4 mg L⁻¹ were recorded in August 1999 and June 2000.

In January 1999 and 2000, chlorophyll a increased with a concomitant decrease in FRP, until FRP was below detectable levels (0.01 mg L⁻¹). In 1999, although FRP was below detectable levels from January-June high chlorophyll a concentrations were supported for two months after FRP decreased below the minimum level of detection. However, in 2000 once FRP concentrations fell below the level of detection, chlorophyll a steadily declined over the following six weeks to a concentration of about 0.07 mg L⁻¹. Whether this is due to a greater suppression of the internal nutrient load in 2000, due to successful mixer operation is difficult to speculate. The NO₃ concentrations follow a similar trend to FRP and decrease as the chlorophyll a concentration increases.

![Figure 7](image-url) Filterable reactive phosphorus (FRP) and soluble inorganic nitrogen (NO₃) concentrations measured in the surface layer at Location 4 between 1998-2001 in Myponga Reservoir.

Chlorophyll a generally did not vary substantially between Locations 1, 4 and 7 (Figure 8). The highest concentrations were measured in February 1999 (0.015 mg L⁻¹) and 2000 (0.018 mg L⁻¹) and in November 2000 - March 2001 (0.02-0.034 mg L⁻¹).
ARTIFICIAL MIXING FOR DESTRATIFICATION AND CONTROL OF CYANOBACTERIAL GROWTH IN RESERVOIRS

Figure 8 Chlorophyll a concentrations in the surface layer at Locations 1, 4 and 7 between 1998 - 2001 in Myponga Reservoir.

3.1.2 Phytoplankton

A range of algal groups were identified and enumerated from the phytoplankton samples. They consisted of Baccillariophyceae (diatoms), Chlorophyceae (green algae), Cryptophyceae (yellow-brown algae) and Cyanophyceae (cyanobacteria) in order of dominance (Figure 9). A list of the major recorded genera is shown in Table 2. Diatoms consisting predominantly of Cyclotella sp. and Nitzschia sp. were most abundant from February to July 1999 and from January 2000 until the end of monitoring in April 2000. Total biovolumes showed a maximum of 4,322 µL L⁻¹ in April 1999 and 5,493 µL L⁻¹ in April 2000. Green algae were most abundant in summer and autumn, i.e. between January and June 1999 and between January and April 2000. Maximum total biovolumes of 5,081 µL L⁻¹ were found in January 1999 and 1,679 µL L⁻¹ in March 2000. While Scenedesmus sp. was the dominant green, other species included Ankistrodesmus sp., Chlamydomonas sp., Chlorella sp., Dictyosphaerium sp. and Oocystis sp. Yellow-brown algae and cyanobacteria were less abundant with total biovolumes not exceeding 1,462 µL L⁻¹ and 350 µL L⁻¹, respectively.

Figure 9 Changes in the biovolumes of cyanobacteria, green algae, diatoms and yellow-brown algae at Location 4 in Myponga Reservoir.

Yellow-brown algae were mostly found in winter, i.e. from June to September 1999. Yellow-brown algal biovolumes contained the species Chroomonas sp. and Cryptomonas sp. Cyanobacterial
abundance increased simultaneously with that of green algae in January 1999 and 2000 with maximum total biovolumes of 237 µL L\(^{-1}\) and 352 µL L\(^{-1}\), respectively. Cyanobacterial total biovolumes contained the species *Anabaena circinalis*, straight *Anabaena* sp., *Pseudanabaena* sp. and *Phormidium* sp. *Anabaena circinalis* was present in the summer months only. Total cell densities were higher in summer 1999/2000 with 2,186 cells mL\(^{-1}\) on 10 January as compared to summer 1998/1999 with 1,482 cells mL\(^{-1}\) on 5 January 1999. The reservoir was dosed with copper sulphate shortly after these two dates to prevent further growth of *A. circinalis*.

### Table 2 Summary of the major phytoplankton identified in Myponga Reservoir

<table>
<thead>
<tr>
<th>Genus</th>
<th>Bacillariophyceae</th>
<th>Chlorophyceae</th>
<th>Cryptophyceae</th>
<th>Cyanophyceae</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Cyclotella</em></td>
<td><em>Ankistrodesmus</em></td>
<td><em>Chroomonas</em></td>
<td><em>Anabaena circinalis</em></td>
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<tr>
<td></td>
<td><em>Nitzschia</em></td>
<td><em>Chlamydomonas</em></td>
<td><em>Cryptomonas</em></td>
<td>Straight <em>Anabaena</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Chlorella</em></td>
<td></td>
<td><em>Pseudanabaena</em></td>
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<tr>
<td></td>
<td></td>
<td><em>Dictyosphaerium</em></td>
<td></td>
<td><em>Phormidium</em></td>
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<tr>
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<td></td>
<td><em>Oocystis</em></td>
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</tr>
<tr>
<td></td>
<td></td>
<td><em>Scenedesmus</em></td>
<td></td>
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</tbody>
</table>

### 3.1.3 Cyanobacterial (*Anabaena*) growth

Myponga Reservoir is generally well mixed and cyanobacterial concentrations are generally low relative to other species. In early January 2000 the reservoir was well mixed however over a two-week period, between January 7 and 21, there was significant heating of the surface water (Figure 10). This was detected and recorded quite clearly by the thermistor chain deployed at Met1. This resulted in the formation of persistent stratification and the diurnal surface mixed layer (calculated after Sherman et al. 2000), remained shallow (Figure 11).

The effect of this was that the cyanobacteria were not entrained deep into the water column each night and could immediately begin to grow quite rapidly. Coupled with this physical trigger, the accompanying other pre-requisites for growth – light and nutrients were known to be ideal: the euphotic depth in January was 3.6 m (\(k_d=1.22\)) and nutrient concentrations were sufficiently high to support both a rapid growth rate and a high yield (NH\(_4\) = 0.027 mg L\(^{-1}\), FRP = 0.038 mg L\(^{-1}\), TP = 0.051 mg L\(^{-1}\), TKN = 0.98 mg L\(^{-1}\), NO\(_x\) = 0.131 mg L\(^{-1}\)). *Anabaena circinalis* was present under well-mixed conditions in early December but was first detected late in December, albeit at low numbers (Table 3). As the water column became stratified the growth of *A. circinalis* accelerated and by 10 January 2000, the concentration was 3,891 cells mL\(^{-1}\). The mean growth rate between 4 January and 10 January was 0.36 day\(^{-1}\) and concentrations were high enough to present a geosmin threat to the treatment plant.

It can be seen that the on-line temperature information can be used to predict and follow the onset of the “high-risk” conditions for growth of *Anabaena* in this reservoir. The understanding of the processes allows us to identify periods when cyanobacteria may present a threat and the appropriate management strategy can be implemented.
ARTIFICIAL MIXING FOR DESTRATIFICATION AND CONTROL OF CYANOBACTERIAL GROWTH IN RESERVOIRS

Figure 10 Temperature profile at meteorological station 1 at Myponga Reservoir

Figure 11 Diurnal surface layer, defined as the shallowest depth at which the temperature difference between two adjacent thermistors is 0.05 °C or greater.

Table 3 Anabaena circinalis concentrations (cells mL⁻¹) at five locations in Myponga Reservoir. The presence of (−) signifies that A. circinalis was not detected in a 1mL, 10x concentrated sample.

<table>
<thead>
<tr>
<th>Location</th>
<th>21/12/99</th>
<th>29/12/99</th>
<th>4/01/00</th>
<th>10/1/00</th>
<th>18/1/00</th>
<th>25/1/00</th>
</tr>
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<tr>
<td>1</td>
<td>4</td>
<td>9</td>
<td>43</td>
<td>3,891</td>
<td>45</td>
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<td>4</td>
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<td>-</td>
<td>-</td>
<td>2,186</td>
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<td>-</td>
<td>459</td>
<td>448</td>
<td>8</td>
<td>-</td>
</tr>
</tbody>
</table>

3.2 Using physical and nutrient data to predict Anabaena growth

Anabaena was present in Myponga Reservoir during a period of low wind mixing and a shallow surface mixed layer. The mixed depth in combination with the euphotic depth (1 % surface irradiance) data can be used to determine the total carrying capacity of the water body. Monitoring data revealed that the euphotic depth ranged between 2.16 m and 3.6 m in Myponga Reservoir.

The light dose that algae would receive whilst travelling through a water column is dependent upon several factors such as the light absorption characteristics of the water body, angle of the sun, wave reflectance and the mixed depth.
In January 1999, the light dose experienced by an algae circulating within the euphotic zone was approximately 10.28 mol m\(^{-2}\) day\(^{-1}\) and the average sub-surface irradiance was 47.8 mol m\(^{-2}\) day\(^{-1}\). The daily light dose experienced when the mixed depth exceeds the euphotic depth is given in Table 4.

Table 4 Modelled mean daily light dose (mol m\(^{-2}\) day\(^{-1}\)) experienced by phytoplankton circulating through various mixed depths in water-bodies with different euphotic depth and a sub-surface light dose of 47.8 mol m\(^{-2}\) day\(^{-1}\). Shaded cells represent conditions where *Anabaena circinalis* growth would be maximal.

<table>
<thead>
<tr>
<th>Mixed depth (m)</th>
<th>Euphotic depth (m)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.28</td>
<td>18.68</td>
<td>24.43</td>
<td>28.39</td>
</tr>
<tr>
<td>2</td>
<td>5.19</td>
<td>10.28</td>
<td>14.85</td>
<td>18.68</td>
</tr>
<tr>
<td>3</td>
<td>3.46</td>
<td>6.91</td>
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<td>5.19</td>
<td>7.77</td>
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</tr>
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<td>2.08</td>
<td>4.15</td>
<td>6.23</td>
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<td>2.97</td>
<td>4.45</td>
<td>5.93</td>
</tr>
<tr>
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<td>1.30</td>
<td>2.60</td>
<td>3.89</td>
<td>5.19</td>
</tr>
<tr>
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<td>1.15</td>
<td>2.31</td>
<td>3.46</td>
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</tr>
<tr>
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<td>1.04</td>
<td>2.08</td>
<td>3.11</td>
<td>4.15</td>
</tr>
</tbody>
</table>

*Anabaena circinalis* strain ANA-271B was grown in the laboratory (using WC media, 25 °C) at a range of light intensities on a 12:12 light: dark cycle. It is apparent that 0.5 mol m\(^{-2}\) day\(^{-1}\) is required for maintenance of the population size, however, growth increases considerably at higher light dose becoming maximal at approximately 10 mol m\(^{-2}\) day\(^{-1}\) (Figure 12). Correlation of the light-dose/growth rate curve (Figure 12) with the light-dose /Zeu-Zmix model (Table 4) enables prediction of when *Anabaena circinalis* growth rate will be maximal. This occurs when the mixed depth is approximately equal to the euphotic depth.

![Figure 12](image-url)  
*Figure 12* *Anabaena circinalis* growth rate versus light dose

As shown in figure 11, there was a two-week period (7-21 Jan, 2000) where the surface layer was very shallow and *Anabaena* growth rate would have been favoured. The mean abundance of *Anabaena* cells on 10 Jan 2000 was 1,628 cells mL\(^{-1}\) and if we assume a growth rate of 0.5 day\(^{-1}\) then by the next mixing period (21 Jan, 2000) the *Anabaena* cell count would be 2.6 x10\(^{5}\) cells mL\(^{-1}\), assuming no nutrient limitation. However, *Anabaena* has a chlorophyll content of approximately 0.7 pg Chl a cell\(^{-1}\), and if a ratio of Chl a: Phosphorus content of 1:1 is assumed, this means that a population of 2.6 x10\(^{5}\) cells mL\(^{-1}\) would require an available phosphorus pool of about 0.182 mg L\(^{-1}\). At the time of the shallow surface layer the FRP was approximately an order of magnitude lower than this value and consequently an *Anabaena* population would be only likely to reach a maximum of about 2.6 x 10\(^{4}\) cells mL\(^{-1}\).
3.3 Evidence of improved water quality using bubble plume aeration

A review of thermal stratification, DO and iron and manganese was undertaken to assess the effectiveness of bubble plume aeration in Myponga Reservoir. During summer from 1984 to 1994 seasonal temperature stratification was evident. Since deployment of the aerator in 1994, isothermal conditions have been maintained at the sampling site (Figure 13a). However, surface layer heating is evident at other sites in the reservoir outside of the immediate bubble plume, which is consistent with other reservoirs where bubble plume aerators are operating (Visser et al., 1994; Sherman et al., 2000).

Dissolved oxygen (DO) data was available from 1992 to 1997. During the summer of 1992/93 and 1993/94 the DO concentration at 30 m was significantly lower than at the surface (Figure 13b). DO concentrations were below 4 mg L\(^{-1}\) occurred for extended periods during 1992/93 and 1993/94, which provided conditions favourable for manganese resolubilisation. Since aerator operation began in 1994 the DO concentration at 30 m has been maintained above 4 mg L\(^{-1}\).

Prior to 1994 the concentration of iron at 30 m depth was consistently higher than the surface concentrations during summer and autumn (Figure 13c). This coincides with the periods of extreme temperature stratification and low DO in the hypolimnion. Soluble iron at 30 m depth reached a maximum concentration of 2.84 mg L\(^{-1}\) in March 1990. The vertical gradient in iron concentration has decreased since deployment of the bubble plume aerator. The mean concentration of iron at 30 m has decreased from 0.71 mg L\(^{-1}\) in 1986 to 0.345 mg L\(^{-1}\) in 1996, and the large flux events have been eliminated.

Manganese concentrations at 30 m have responded to destratification in a similar manner to iron (Figure 13d). The mean concentration of manganese at 30 m was 0.41 mg L\(^{-1}\) in 1986 and reduced to 0.052 mg L\(^{-1}\) in 1996 due to destratification. The high yearly mean in 1986 was significantly elevated because of the flux from sediments during summer and autumn where the maximum concentration was approximately 1.8 mg L\(^{-1}\). These large flux events observed prior to 1994 have been reduced by operation of the destratifier.

The concentration of iron and manganese in the hypolimnion depends upon the rate of flux from sediment and the duration of stratification. Once the hypolimnion becomes anoxic the conditions suitable to maintain iron and manganese in the soluble form will persist whilst there is little mixing and the hypolimnion remains separated from the atmosphere. To allow a comparison between years the duration of stratification was quantified as number of days per year (July–June) where the temperature difference between 10 m and 30 m was greater than 1ºC. Measurements were generally taken in the morning, however, the temperature difference between 10 m and 30 m was selected as the best indicator of persistent stratification as this avoids confounding effects due to diurnal surface heating, and time of sampling.

There was a temperature difference of greater than 1ºC for 224 days in the year 1985/86 which gave rise to maximum iron and manganese concentrations of 2.55 mg L\(^{-1}\), 1.8 mg L\(^{-1}\), respectively (Table 5). In the year 1995/96 there were only 28 days where thermal stratification between 10 m and 30 m occurred and consequently the maximum iron and manganese concentrations were low; 0.386 mg L\(^{-1}\) and 0.087 mg L\(^{-1}\), respectively. The yearly maximum concentration of iron at 30 m was significantly correlated with the duration of stratification (Spearman non-parametric correlation, \(r_s=0.7328\), \(P=0.0044\)). The maximum manganese concentration was also significantly correlated with the duration of stratification (Spearman non-parametric correlation \(r_s=0.8303\), \(P=0.0004\)). The yearly maximum manganese concentration correlated with the yearly maximum iron concentrations (Spearman non-parametric correlation \(r_s=0.9133\), \(P<0.0001\)) indicating that manganese resolubilisation coincided with iron resolubilisation.

The bubble plume aerator deployed in Myponga Reservoir has been successful in reducing the concentration of soluble iron and manganese in the water column. These ions increase treatment costs and contribute to ‘dirty water’ problems during distribution. According to the Australian Drinking Water Guidelines (1996) the concentration of iron in drinking water should not exceed 0.3 mg L\(^{-1}\). This guideline is based upon the concentration at which iron precipitates from solution and the taste threshold. Prior to the installation of a destratifier at Myponga Reservoir the soluble iron concentration
frequently exceeded the guideline. However, since aerator operation the iron concentration is maintained closer to the guideline concentration.

Based upon aesthetic considerations the concentration of manganese in drinking water should not exceed 0.1 mg L$^{-1}$ (Australian Drinking Water Guidelines, 1996). The bubble plume aerator at Myponga has been successful at maintaining manganese concentrations below this level. Manganese would not be considered a health threat unless the concentration exceeded 0.5 mg L$^{-1}$, a level that has not occurred since the installation and operation of the aerator.
Figure 13 Temperature at the surface, 10 m, 20 m and 30 m depth (a) DO concentrations at surface and 30 m (b), soluble iron at the surface and 30 m (c) and soluble manganese at surface and 30 m (d). All samples were taken adjacent to the offtake tower.
Table 5 Duration of persistent thermal stratification (temperature difference between 10 m and 30 m >1ºC) and the maximum iron and manganese concentrations measured at 30 m in Myponga Reservoir.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of days where temperature difference between 10 m and 30 m &gt;1ºC</th>
<th>Maximum soluble iron concentration (mg L⁻¹)</th>
<th>Maximum soluble manganese concentration (mg L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984/85</td>
<td>119</td>
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<tr>
<td>1985/86</td>
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</tr>
<tr>
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<tr>
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<tr>
<td>1996/97</td>
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</tr>
</tbody>
</table>

3.4 Evaluation of surface mechanical mixers

3.4.1 Flow measurements

Measurements of tangential and vertical flow were made at the exit of the surface mixer draft tube radial. Figure 14 shows the vertical and radial flow through the water column at 3.8 m from the centre of the surface mixer. Negative horizontal flow radiates away from the surface mixer and negative vertical velocity downwards. The profile was recorded on the 28/08/2000 where a 2ºC temperature difference existed between the SML and the hypolimnion. The depth of the diurnal thermocline was ~1.5 m. The flow represented a swirling buoyant plume. A horizontal intrusion formed when the plume reached a level of neutral buoyancy at ~7 m below the surface.

![Figure 14](image)

Figure 14 Acoustic Doppler Velocimeter (ADV) measurements at 3.8 m from the centre of the 800 m surface mixer

To determine the penetration depth of the exiting flow a propeller meter was vertically mounted on a bracket and lowered underneath the draft tube. Measurements were recorded across the diameter of the draft tube at 0.3 m intervals. The measurements were carried out on the 26/9/2000 where a 4ºC temperature difference existed between the surface and reservoir bottom. The depth to which the flow
penetrated was ~ 1.8 m where no significant flow was detected (Figure 15). The flow profile measured immediately at the draft tube exit shows a typical flow pattern downstream of an impeller.

![Figure 15](image-url) Averaged mean water draft tube exit velocity, measure directly below the draft tube.

Temperature profiling recorded on the 19/02/2001 taken at regular intervals away from the surface mixer supported the plume hypothesis. Figure 16 shows the exiting flow from the draft tube forming a horizontal intrusion. The plots in Figure 16 are from 7, 9, 16 and 55 m from the centre of the surface mixer. The plume achieves neutral buoyancy at ~7 m below the surface at approximately 30 m from the surface mixer.

![Figure 16](image-url) Temperature profiles taken on 19/02/2001, from left to right recorded at 7, 9, 16 and 55 m from the surface mixer. The surface temperature was 24.5°C and the bottom temperature was 21.8°C.

### 3.4.2 Simulation of surface mixer algorithm with DYRESM

Myponga Reservoir was simulated from September 1999 to August 2000 using hourly averaged meteorological data generating a daily output at 12:00 h. During January 2000 permanent stratification existed at Myponga Reservoir for a period of two weeks and the threat of excessive cyanobacteria growth existed. This is the critical period for the surface mixers to have an impact. A comparison of the measured temperature profile to the simulated data taken at 12:00 h on the 18/01/2000 is shown in Figure 17. The temperature profile was taken from meteorological station 1 (36 m).
The simulation adequately represented the temperature structure in the modelled period. The example shown in Figure 17 demonstrates that with the use of the surface mixer and aerator algorithms DYRESM was able to capture the physical structure with the simulated thermocline corresponding to the observed data. Similar comparisons were made at daily intervals and the same degree of accuracy was observed. With the successful visual validation of the surface mixer algorithm the different combinations of aerator/surface mixer operation could be investigated with confidence.

### 3.4.3 Simulating the operation of the aerator and surface mixers in Myponga Reservoir

#### 3.4.3.1 Dissolved Oxygen

The simulation of artificial mixing and dissolved oxygen levels in Myponga Reservoir are shown in Figure 18. The DO concentrations were maintained at levels greater than 4 to 5 mg L\(^{-1}\) throughout the entire simulated period which also occurred in the observed data. When the reservoir was naturally fully mixed, DO was maintained at levels exceeding 5 mg L\(^{-1}\), and during periods of high insolation when artificial mixing was used, the high levels of DO were maintained.
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Figure 18 Simulated DO profiles for the period September-1999 to September-2000, under artificially mixed conditions. Note: the period when surface mixers and aerator were both operated is marked with a solid black line.

3.4.3.2 Phytoplankton

The model was used to compare simulated and observed phytoplankton population data from Myponga Reservoir. The observed phytoplankton data was obtained from the monitoring program (integrated samples from the top 5 m of the water column). The simulated data is presented in the same integrated format, i.e. simulated daily concentrations are averaged over the top 5 m. The comparison of measured and simulated total Chl a concentration for the simulated period, where a $R^2$ and $P$-value of 0.75 and 3E-09 respectively were obtained, is shown in Figure 19. The correlation was the best achieved using the calibration method described above. The $R^2$ and $P$-value obtained indicated a reasonably strong correlation between observed and simulated data, which was also supported by visual inspection.

To maintain the calibration parameters within a reasonable range of their published values and accurately reproduce the total Chl a concentration for the modelled period proved to be difficult. All of the parameters were found to be sensitive and slight changes in their values and this produced dramatic changes in the simulation.

Figure 19 A comparison of observed and simulated total Chl a concentration ($\mu$g Chl a L$^{-1}$) in Myponga Reservoir from September 1999 – August 2000. The figure shows simulated CuSO$_4$ dosing on 11 and 12-January-2000, and surface mixers and aerator operation between 1-October-1999 and 1-April-2000. The $R^2$ and $P$-value for the comparison were 0.75 and 3E-09, respectively.
The model over-predicted the total Chl a concentration for the simulated period, which could not be rectified without completely inhibiting the growth of the cyanobacteria and diatoms due to the dominance of the greens. The artificial mixed conditions at Myponga Reservoir and the dominance of the greens, as seen in the field data (Figure 9), resulted in the minimal growth of cyanobacteria, with the maximum concentration of *Anabaena circinalis* peaking at ~ 1.2 µg Chl a L⁻¹ (~ 1,600 cells mL⁻¹).

Phytoplankton concentrations at this low level are inherently very difficult to simulate, especially when other simulated groups dominate and grow to concentrations that are orders of magnitude greater. Subsequently the model output was accepted as a reasonable representation of the phytoplankton assemblage observed in Myponga Reservoir under artificially mixed conditions, which included CuSO₄ dosing.

The individual phytoplankton groups were analysed using the measured and simulated total chlorophyll data. The total Chl a concentration for the three simulated phytoplankton groups represented the entire phytoplankton assembly in Myponga Reservoir, i.e. the sum of the individual Chl a concentration for the three groups was equal to the total Chl a concentration of the phytoplankton assembly. Using individual and total Chl a concentrations the percentage contribution for each group was determined (Appendix I).

The observed phytoplankton community at Myponga Reservoir was dominated by greens (96.3% of the total biomass measured as Chl a) for the entire monitoring period and was accurately reproduced in the model simulation with greens dominating 96.6% of the total biomass (Figure 20). The relationship between observed and simulated data was a $R^2$ and $P$-value of 0.73 and 4E-09, respectively.

The comparison between observed and simulated *Anabaena circinalis* chlorophyll concentration is shown in Figure 21. The observed peak 1.2 µg Chl a L⁻¹ (~1,600 cells mL⁻¹) which occurred on 10 January 2000, was not reproduced in the simulation as a result of simulated copper sulphate dosing and due to a low cell concentration. Although, the observed concentration represented 0.5% of the total biomass, the simulated concentration represented 0.8% of the total biomass. The correlation between observed and simulated data was a $R^2$ and $P$-value of 0.55 and 0.009, respectively.

![Figure 20](image-url) Observed and simulated occurrence of the green alga *Scenedesmus* (concentration in µg Chl a L⁻¹) in Myponga Reservoir from September 1999 – August 2000, with a $R^2$ and $P$-value of 0.73 and 4E-09, respectively.
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Figure 21 Comparison of the observed and simulated occurrence of the cyanobacterium *Anabaena circinalis* in Myponga Reservoir from September 1999 – August 2000 (concentration in µg Chl a L⁻¹), with a $R^2$ and $P$-value of 0.55 and 0.009, respectively.

The observed growth of *Nitzschia* sp. was not accurately reproduced in the simulation (Figure 22). In particular, the model did not capture the occurrence of a single peak in late March/early April. However, the observed diatom concentration represented 3.2 % of the phytoplankton biomass, while the model output simulated 2.7 % of the total biomass (measured as Chl a). Modelling also showed that *Nitzschia* sp. growth would persist at a low concentration.

Figure 22 Observed and simulated occurrence of the diatom *Nitzschia* sp. in Myponga Reservoir from September 1999 – August 2000 (concentration in µg Chl a L⁻¹).

To further validate the DYRESM-CAEDYM simulation of the phytoplankton community, the modelled period was extended from September 2000 to March 2001. The observed and simulated total Chl a concentrations for the extended period are shown in Figure 23. The simulated biomass captures the timing of the summer peak that was observed in the field data, but did not simulate what is regarded as an atypical or unseasonal peak that occurred in December 2000. This peak was attributed to the excessive growth of *Chroomonas* sp., a species which was not included in the model. The simulated growth of *Anabaena circinalis* from September 2000 to March 2001 produced a reasonable match with
the observed field data (Figure 24), although the simulated growth started earlier in the season than was observed in the actual reservoir monitoring data.

![Figure 23](image)

**Figure 23** A comparison of observed and simulated total Chl a concentration (µg Chl a L⁻¹), with simulated CuSO₄ dosing on 31 January 2000, and surface mixers and aerator operating between the 1 October 2000 and 28 February 2001.

![Figure 24](image)

**Figure 24** Comparison between the observed and simulated *Anabaena circinalis* concentration (µg Chl a L⁻¹) from 1 September 2000 to 1 March 2001.

The simulation of the 3 types of phytoplankton that were representative of the assembly in Myponga Reservoir from September 1999 to March 2001 produced reasonable results considering the restrictions of the model. The observed phytoplankton community consisted of more than three species simulated in this model (Table 2). Other species will dominate with changes in nutrients, light and temperature as highlighted by the excessive growth of *Chroomonas*. An improvement to the CAEDYM model would be to increase the number of species simulated, although this would require intensive calibration and a trial and error approach as used in this study would be insufficient. An alternative method that will be explored in the future will be to use non-linear parameter fitting software such as NLFIT (Kuczera and Parent, 1998).
3.5 Simulation of various management strategies

The CAEDYM model output compared with observed field data gave a reasonable representation of phytoplankton biomass (as total Chl a) for three species in Myponga Reservoir. The comparison between observed and simulated data for Scenedesmus showed a strong correlation whereas a moderate correlation was observed with Anabaena circinalis. The next step involved using the model to determine the individual and combined impact of the surface mixers and aerator for destratification and control of cyanobacteria. The following strategies were investigated for their ability to maintain DO greater than 4 mg L\(^{-1}\) and to limit Anabaena circinalis below 2,000 cells mL\(^{-1}\).

1. No artificial intervention
2. Aerator and surface mixers with no CuSO\(_4\) dosing
3. Aerator only
4. Surface mixers at the actual measured flow rate (3.5 m\(^3\) s\(^{-1}\))
5. Surface mixers at design flow rate (5 m\(^3\) s\(^{-1}\))
6. Surface mixers at increased flow rate (8 m\(^3\) s\(^{-1}\))
7. Intermittent operation
8. Equivalent aerator energy input using surface mixers

3.5.1 No artificial intervention (Strategy 1)

The simulation of Myponga Reservoir with no artificial mixing for the period of 1 September 1999 to 1 September 2000 illustrated that permanent stratification would exist for several months (Figure 25). The stratification caused DO levels in the hypolimnion to decrease below 4 mg L\(^{-1}\) for approximately six months from mid-spring to mid-autumn.

![Figure 25](image)

**Figure 25** Simulated thermal structure and DO concentration for Myponga Reservoir with no artificial mixing. The figure shows isopleths for temperature and DO over the full depth of the reservoir for a 1-year period, September, 1999 - August, 2000.

The simulation of Anabaena circinalis growth showed that the number of cells would reach 4,400 cells mL\(^{-1}\) in mid-April and have a mean concentration of 1,000 cells mL\(^{-1}\) (Figure 26). These simulation results highlight the potential degradation of water quality that could occur without the use of artificial mixing. However, it is worth noting that if green algae were to dominate earlier in the summer season, nutrient concentrations may decrease which could potentially lead to nutrient-limited growth of other species including cyanobacteria later in the season.
3.5.2 Artificial Mixing with no CuSO₄ dosing (Strategy 2)

The use of artificial mixing with no CuSO₄ dosing in the simulation resulted in a slightly increased *Scenedesmus* biomass and a decreased correlation with the observed data (Figure 27). The simulated single summer bloom occurred at the appropriate time compared with observed data. The influence of artificial mixing with no CuSO₄ on *Anabaena circinalis* is shown in Figure 28. The model simulation indicates that cell numbers would approximate 300 cells mL⁻¹ for approximately 6 months, while the maximum concentration would reach 1,100 cells mL⁻¹ or 0.78 mg Chl a L⁻¹.

Figure 26 Simulated *Anabaena circinalis* concentration (µg Chl a L⁻¹) with no artificial mixing compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

Figure 27 Simulated *Scenedesmus* concentration (µg Chl a L⁻¹) with no CuSO₄ dosing compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000. \( R^2 = 0.72 \).
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Figure 28 Simulated *Anabaena circinalis* concentration (µg Chl a L⁻¹) with no CuSO₄ dosing compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

3.5.3 Aerator only (Strategy 3)

The DYRESM-CAEDYM model was run with only the aerator algorithm, which was operational between 1 October 1999 and 1 April 2000. The temperature profile and DO profiles indicate that mixed conditions were maintained for the majority of the simulated period (Figure 29), with stratification limited to a couple of weeks during late February. The DO concentrations were maintained at greater than 4 mg L⁻¹, although some DO depletion is evident towards late April at the sediment surface. The simulated growth of *Scenedesmus* produced a lower total biomass (92.9%) without the combined use of the surface mixers, and the timing of growth was unchanged compared with growth under normal operating conditions (Figure 30). The growth of *Anabaena circinalis* increased substantially and accounted for 4.0% of the total biomass (Figure 31). A maximum peak of 1.0 µg Chl a L⁻¹ or 1400 cells mL⁻¹ occurred in mid April. As with the previous strategies, sustained growth of *Anabaena* was maintained, but with a higher mean concentration of ~450 cells mL⁻¹.
Figure 29 Simulated thermal structure and DO concentration for Myponga Reservoir for operation with the aerator only (period when aerator operating is marked with a solid black line). The figure shows isopleths for temperature and DO over the full depth of the reservoir for a 1-year period, September, 1999 - August, 2000.

Figure 30 Simulated Scenedesmus concentration (μg Chl a L⁻¹) with the use of the aerator only compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.
3.5.4 Surface Mixers at the actual Measured Flow Rate (Strategy 4)

The use of the surface mixers alone operating at their measured individual flow rate of 3.5 m$^3$ s$^{-1}$ were not capable of maintaining fully mixed conditions (Figure 32). Significant stratification occurred during the summer months, which was reflected in the DO profile with concentrations falling below 3.0 mg L$^{-1}$ at the sediment surface. DO at this level would cause deleterious water quality conditions.

The timing and magnitude of the simulated growth of Scenedesmus was significantly different to the observed data (Figure 33). Scenedesmus grew earlier in the summer period, peaking at the beginning of December 1999 which was similar to the simulated growth with no mixing (Strategy 1). Anabaena circinalis growth also started earlier than that in the previous scenarios, with persistent and significant
growth occurring early autumn (Figure 34). The maximum concentration of *Anabaena circinalis* was ~ 2,400 cells mL\(^{-1}\), with a mean concentration of ~ 680 cells mL\(^{-1}\). These results indicate that the sole use of the surface mixers operating at 3.5 m\(^3\) s\(^{-1}\) are not able to limit the growth of *Anabaena circinalis* and associated geosmin production could become problematic in the water supply.

![Figure 33](image)

**Figure 33.** Simulated *Scenedesmus* concentration (\(\mu\)g Chl a L\(^{-1}\)) with the use of the surface mixers operating at 3.5 m\(^3\) s\(^{-1}\) each compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

![Figure 34](image)

**Figure 34** Simulated *Anabaena circinalis* concentration (\(\mu\)g Chl a L\(^{-1}\)) with the use of the surface mixers operating at 3.5 m\(^3\) s\(^{-1}\) each compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

### 3.5.5 Surface Mixers at 5 m\(^3\) s\(^{-1}\) (Strategy 5)

Increasing the flow rate of the surface mixers to 5 m\(^3\) s\(^{-1}\) improved their destratification ability and decreased the temperature gradient through the water column (Figure 35). DO was maintained at concentrations greater than 4 mg L\(^{-1}\) throughout the simulated period. As with the use of the surface mixers alone operating at 3.5 m\(^3\) s\(^{-1}\), the growth of *Scenedesmus* occurred earlier in the season with
similar magnitude (Figure 36). *Scenedesmus* contributed 95.3% of the total biomass (as Chl a). When the two surface mixers operated at 5 m$^3$ s$^{-1}$, *Anabaena circinalis* peaked at a cell concentration of ~1,500 cells mL$^{-1}$ or 1.12 µg Chl a L$^{-1}$ in mid-April 2000, and persisted with a mean concentration of ~480 cells mL$^{-1}$ (Figure 37). The sustained growth of cyanobacteria would require additional intervention to maintain water quality.

Figure 35 Simulated thermal structure and DO concentration for Myponga Reservoir for operation of the two surface mixers at a simulated flow rate of 5 m$^3$ s$^{-1}$. Note the period when surface mixers were operational is marked with a solid black line. The figure shows isopleths for temperature and DO over the full depth of the reservoir for a 1-year period, September, 1999 - August, 2000.

Figure 36 Simulated *Scenedesmus* concentration (µg Chl a L$^{-1}$) with the use of the surface mixers operating at 5 m$^3$ s$^{-1}$ each compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.
Figure 37 Simulated *Anabaena circinalis* concentration (μg Chl a L⁻¹) with the use of the surface mixers operating at 5 m³ s⁻¹ each compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

### 3.5.6 Surface mixers at 8 m³ s⁻¹ (Strategy 6)

Simulation of a further increase in surface mixer flow rate to 8 m³ s⁻¹ resulted in a decrease in stratification and an increase in DO levels above 4 mg L⁻¹ throughout the water column (Figure 38). However, the timing and magnitude of *Scenedesmus* growth was similar to when the surface mixers were operated at the lower flow rates (Strategies 4 and 5), with growth occurring in late spring (Figure 39). *Scenedesmus* also maintained their dominance contributing to 96.4% of the total biomass. The timing of *Anabaena circinalis* growth was also similar to strategies 4 and 5, however the mean concentration was significantly reduced to ~ 330 cells mL⁻¹, with a maximum peak of ~ 1,000 cells mL⁻¹ or 0.73 μg Chl a L⁻¹ occurring mid-April (Figure 40). With the use of the surface mixers alone running at 8 m³ s⁻¹, the growth of *Anabaena circinalis* was maintained at manageable levels and additional intervention involving CuSO₄ could be avoided.

Figure 38. Simulated thermal structure and DO concentration for Myponga Reservoir for operation of the two surface mixers at a simulated flow rate of 8 m³ s⁻¹. Note the period when surface mixers were operational is marked with a solid black line. The figure shows isopleths for temperature and DO over the full depth of the reservoir for a 1-year period, September, 1999 - August, 2000.
**ARTIFICIAL MIXING FOR DESTRATIFICATION AND CONTROL OF CYANOBACTERIAL GROWTH IN RESERVOIRS**

**Figure 39** Simulated *Scenedesmus* concentration ($\mu$g Chl a L^{-1}) with the use of the surface mixers operating at 8 m$^3$s^{-1} each compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

**Figure 40** Simulated *Anabaena circinalis* concentration ($\mu$g Chl a L^{-1}) with the use of the surface mixers operating at 8 m$^3$s^{-1} each compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

**3.5.7 Intermittent operation (Strategy 7)**

Intermittent operation of artificial mixing has been shown to be effective in managing phytoplankton by preventing any one group of species to become dominant (Reynolds et al., 1994). To test a similar scenario for Myponga Reservoir the aerator and surface mixers (at 3.5 m$^3$s^{-1}) were operated intermittently in the DYRESM-CAEDYM model for the period 1 December-1999 to 19 April 2000. This period of operation was initially based upon the corresponding dates of anoxic periods, but was further refined to reduce the number of days that artificial mixing would be required. The surface mixers and aerators were switched on for an arbitrary period of 2 days every 4 days throughout the operational period. The temperature profile in Figure 41 shows a similar trend as when the surface mixers and aerators were run continuously and the DO concentration was adequately maintained throughout the modelled period. The growth of *Scenedesmus* occurred early in December, which was similar to the
simulated results that were produced when the surface mixers were operated alone at various flow rates (Figure 42). The growth of *Anabaena circinalis* also occurred at a similar time as when the surface mixers were operated alone (Figure 43). However, with intermittent mixing the magnitude of *Anabaena circinalis* growth was significantly reduced with a maximum peak of ~670 cells mL$^{-1}$ or 0.48 µg Chl a L$^{-1}$ occurring in mid-April and a mean concentration of 235 cells mL$^{-1}$. Simulating intermittent operation of the surface mixers and aerator shows that there is some potential in this management strategy aimed at reducing costs as isothermal conditions were maintained and *Anabaena circinalis* concentrations were kept below 2,000 cells mL$^{-1}$.

**Figure 41** Simulated thermal structure and DO concentration for Myponga Reservoir using intermittent mixing with the operation of both the surface mixers at 3.5 m$^3$ s$^{-1}$ and the aerator. The mixing devices operate intermittently (2 days on, 4 days off) throughout the period marked with a solid black line. The figure shows isopleths for temperature and DO over the full depth of the reservoir for a 1-year period, September, 1999 - August, 2000.

**Figure 42** Simulated *Scenedesmus* concentration (µg Chl a L$^{-1}$) with the use of intermittent artificial mixing compared with the observed data under normal operating conditions. Simulated *Scenedesmus* concentration (µg Chl a L$^{-1}$) with the use of intermittent artificial mixing compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.
ARTIFICIAL MIXING FOR DESTRATIFICATION AND CONTROL OF CYANOBACTERIAL GROWTH IN RESERVOIRS

3.5.8 Equivalent aerator energy input using surface mixers (Strategy 8)

The final strategy that was investigated was related to the energy requirements of the bubble plume aerator (100 kW) versus the surface mixers (4 kW). Based on energy consumption, 25 surface mixers (3.5 m$^3$ s$^{-1}$) would equate to the current single bubble plume aerator. The DYRESM-CAEDYM was run with 25 surface mixers which resulted in fully mixed conditions and DO concentrations above 4 mg L$^{-1}$ (Figure 44). Using this strategy, the growth of Scenedesmus started early in November and dominated the biomass with a 98.3% contribution (Figure 45). The growth of Anabaena circinalis was almost insignificant, but persisted all year with a mean concentration of ~80 cells mL$^{-1}$ or 0.06 µg Chl a L$^{-1}$ and a maximum concentration of ~150 cells mL$^{-1}$ or 0.11 µg Chl a L$^{-1}$ (Figure 46).

Figure 43 Simulated Anabaena circinalis concentration (µg Chl a L$^{-1}$) with the use of intermittent artificial mixing compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

Figure 44 Simulated thermal structure and DO concentration for Myponga Reservoir for the operation of 25 surface mixers (100 kW energy input) at a simulated flow rate of 3.5 m$^3$ s$^{-1}$. Note the period when surface mixers were operational is marked with a solid black line. The figure shows isopleths for temperature and DO over the full depth of the reservoir for a 1-year period, September, 1999 - August, 2000.
Figure 45 Simulated *Scenedesmus* concentration (μg Chl a L\(^{-1}\)) with the use of 25 surface mixers (100 kW energy input) compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

Figure 46 Simulated *Anabaena circinalis* concentration (μg Chl a L\(^{-1}\)) with the use of 25 surface mixers (100 kW energy input) compared with the observed data under the conditions that the reservoir was operated for the 1-year period, September, 1999 - August, 2000.

The effectiveness of the various operational strategies used to limit the growth of *Anabaena circinalis* and maintain DO concentration in the water column are summarised in Table 6. The simulation employed for validation, including the surface mixers, bubble plume aerator and CuSO\(_4\) dosing algorithms, produced similar results to the observed field data. If no artificial mixing or CuSO\(_4\) dosing was undertaken, excessive growth of *Anabaena circinalis* would occur and permanent stratification would lead to the presence of anoxic conditions. The use of the aerator alone without CuSO\(_4\) dosing adequately maintained well-mixed conditions and DO throughout the water column. However, the growth of *Anabaena circinalis* could exceed 1,000 cells mL\(^{-1}\) (for a total of 16 days) but would not reach the threshold of 2,000 cells mL\(^{-1}\).
When the aerator is coupled with the surface mixers (at 3.5 m³ s⁻¹), the growth of *Anabaena circinalis* was further reduced with the peak concentration falling from ~ 1,400 cells mL⁻¹ to ~ 1,000 cells mL⁻¹. The operation of the surface mixers at actual measured flow rates (3.5 m³ s⁻¹) alone would not be able to destratify the water column and maintain DO at acceptable levels, and importantly the growth of *Anabaena circinalis* would exceed 2,000 cells mL⁻¹. Increasing the flow rates of the surface mixers improved their destratification ability and reduced the growth of *Anabaena circinalis*. With a surface mixer flow-rate of 8 m³s⁻¹, optimal results were achieved maintaining DO above 4 mg L⁻¹ and limiting the maximum concentration of *Anabaena circinalis* to ~ 1,000 cells mL⁻¹.

Using intermittent mixing, the growth of cyanobacteria was restricted to a maximum concentration of ~ 700 cells mL⁻¹ and well-mixed conditions were maintained. The use of CuSO₄ dosing would not be required under this strategy and operational costs would be reduced due to the increased downtime of the aerator and surface mixers. The use of 25 surface mixers, using the same energy as the existing aerator, adequately destratified Myponga Reservoir and almost completely inhibited the growth of *Anabaena circinalis*.

<table>
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<th>Artificial mixing operation</th>
<th>Maximum cyanophyte concentration (cells mL⁻¹)</th>
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<th>Minimum DO (mg L⁻¹)</th>
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**Table 6** Comparison of results from existing and simulated water quality management strategies.
4 SUMMARY AND RECOMMENDATIONS

4.1 On-line monitoring

On-line monitoring in reservoirs is not widely practised in distinct contrast to monitoring and automation of water treatment plant processes. Knowledge of how hazards including nuisance cyanobacterial growth develop in reservoirs is critical if they are to be effectively managed. The key to developing an enhanced monitoring system for real-time hazard detection is firstly, understanding reservoir hydrodynamics and secondly integrating the required on-line physical and chemical data and routine data with an understanding of the ecological, chemical and physical processes. A process flow chart of these steps is shown in Figure 47. Examples of background historical system knowledge would include understanding seasonal hydrology and knowing the nutrient status and stratification behaviour of the reservoir. On-line monitoring consists of automatic flow gauging on inflow streams, high resolution thermistor chains in the reservoir and dissolved oxygen sensors at depth adjacent to bottom sediments. In its most advanced form, monitoring can be linked to hydrodynamic and ecological models to provide extra decision support by predictive modelling of stratification, DO levels, algal growth and metal resolubilisation.

Figure 47 Conceptual framework for monitoring for hazard and risk assessment in reservoirs.
ARTIFICIAL MIXING FOR DESTRATIFICATION AND CONTROL OF CYANOBACTERIAL GROWTH IN RESERVOIRS

4.2 Monitoring study: lessons from Myponga Reservoir

The monitoring study of Myponga Reservoir provided valuable physical, chemical and biological data, which can be incorporated into the management of the reservoir. The key findings for the study period were:

- Myponga Reservoir is a moderately eutrophic water body before the onset of summer, and nutrient concentrations vary with season as a result of rainfall (inflow) and phytoplankton growth. Winter rainfall provides the suitable chemical environment for phytoplankton growth with phosphorus (FRP) and nitrogen (NOx) concentrations reaching up to 0.04 and 0.016 mg L\(^{-1}\), respectively. In summer, nutrients in the water column are depleted by phytoplankton growth. Total chlorophyll concentrations ranged from 0.001 to 0.023 mg L\(^{-1}\).
- The phytoplankton community is diverse but generally dominated by the green algae, *Scenedesmus* and the diatom *Nitzschia*. *Anabaena circinalis* was evident later in the phytoplankton succession.
- Meteorological data showed that although the reservoir is mostly well mixed with the mixed depth exceeding the euphotic depth, there are several weeks when the reservoir stratifies and is vulnerable to *Anabaena circinalis* growth.
- *Anabaena circinalis* growth coincided with a shallow surface mixed layer and is likely when the mixed depth approximates the euphotic depth.

4.3 Evaluation of artificial mixing

The addition of the surface mixer and CuSO\(_4\) dosing algorithms to DYRESM-CAEDYM enabled the phytoplankton succession and DO concentration to be adequately simulated and validated against observed field data for the period 1 September 1999 to 1 September 2000. This enabled various management strategies to be investigated. Modelling showed that the threat of growth of the nuisance cyanobacterium *Anabaena circinalis* would exist during periods of thermal stratification combined with a shallow surface mixed layer, coinciding with depleted oxygen levels in the hypolimnion and adequate nutrient concentrations (FRP > 0.01 mg L\(^{-1}\) and NOx > 0.1 mg L\(^{-1}\)).

The current aerator-based mixing system at Myponga Reservoir adequately maintains DO throughout the water column, and coupled with CuSO\(_4\) dosing, limits the growth of *Anabaena circinalis* to a maximum concentration of ~ 1,600 cells mL\(^{-1}\) or 1.17 µg Chl a L\(^{-1}\) (0.5% of the total biomass as Chl a). The simulation of the existing aerator, surface mixers and CuSO\(_4\) dosing produced similar results, reinforcing the need for intervention to maintain manageable levels of cyanobacteria and DO concentrations. The simulation showed that when the surface mixers and aerator are used without the use of CuSO\(_4\) dosing (strategy 2) the *Anabaena circinalis* would not exceed concentrations that would be of concern for water supply. The use of the surface mixers alone was found to be adequate at maintaining water quality if the flow rate could be increased to 8 m\(^3\) s\(^{-1}\). However, at their measured flow rate (3.5 m\(^3\) s\(^{-1}\)) they are unable to fully destratify Myponga Reservoir and limit the growth of *Anabaena circinalis* to below 2,000 cells mL\(^{-1}\).

The use of intermittent artificial mixing would reduce operational costs as the aerator and surface mixers would operate for 50% less time than the current operational schedule. Using this technique, destratified conditions are maintained, DO concentrations are kept high and the growth of *Anabaena circinalis* is minimal and importantly, the use of CuSO\(_4\) dosing is not necessary. Under the current operating conditions, the simulation demonstrated that the use of CuSO\(_4\) dosing is not necessary, as *Anabaena circinalis* concentrations did not exceed 2,000 cells mL\(^{-1}\). As demonstrated with DYRESM-CAEDYM, the current nutrient concentrations, light climate, meteorological forcing and artificial mixing operations at Myponga Reservoir do not favour the excessive growth of *Anabaena circinalis*.

The successful simulation of Myponga Reservoir with the DYRESM-CAEDYM model demonstrates that modelling is an effective tool to assess and optimise water quality management strategies. Upon successful simulation of the limnological processes in a water body, a range of options and strategies can be evaluated. The modeller can alter meteorological conditions, nutrient loadings, timing and use of artificial mixing devices to gain insight into the management of the water body. The addition of the surface mixer and CuSO\(_4\) dosing algorithms has successfully been incorporated into the DYRESM-CAEDYM model within this project and this has increased the utility of the models for management studies in drinking water reservoirs.
5 PUBLICATIONS FROM THIS RESEARCH

The following publications are a result of research related to the investigation into artificial mixing for destratification and control of cyanobacteria. The publications are broadly grouped into reservoir management, artificial destratification and phytoplankton physiology/ecology.

5.1 Reservoir Management


5.2 Reservoir hydrodynamics


5.3 Phytoplankton physiology and ecology


6 ACKNOWLEDGMENTS

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7 REFERENCES


Table 1 Parameter values used for phytoplankton growth in CAEDYM. (1Field data, Chapter 4 Lewis 2003; 2Westwood and Ganf, 2002; 3Brookes et al. 1999a; 4Kirk, 1994; 5Reynolds 1984; 6Chen and Lu, 2002; 7Reynolds et al., 2001; 8Bierman and Dolan, 1981; 9Griffin et al., 2001; 10Riley and Stefan, 1987).

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