Numerical Simulation of Surface Mixers used for Destratification of Reservoirs

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Abstract: An algorithm describing the flow for a plane plume was incorporated into the DYRESM one-dimensional hydrodynamic model, to simulate the action of raft mounted mechanical surface mixers with draft tube diffusers (hereafter referred to as surface mixers). The algorithm was validated against extensive physical field data collected at an artificially mixed South Australian water supply reservoir. The use of surface mixers for destratification and control of algal growth is becoming increasingly popular, however, minimal research has been undertaken to determine the effectiveness and efficiency of such systems compared to more established methods such as bubble plume aerators. Two surface mixers have been installed at Myponga reservoir to destratify and control the growth of cyanobacteria. Field measurements on the exiting flow from the surface mixers, using an Acoustic Doppler Velocimeter (ADV) indicated the presence of an azimuthal velocity, which sets up radial and axial pressure gradients. The near-field ADV measurements show a spreading flow from the bottom of the draft tube, where the adverse axial pressure gradient causes axial deceleration, representing a swirling plume. The effects of surface mixers on controlling water quality problems associated with summer stratification, as compared to other methods of destratification or other management strategies, are being investigated with DYRESM, and recommendations made based on specific problems.

Keywords: Surface mixers; Destratification; DYRESM; Modelling; Cyanobacteria

1. INTRODUCTION

Excessive input of nutrients to water bodies is recognised as a major pollution problem in the aquatic environment throughout the world, causing deterioration in water quality. The resultant eutrophication leads to overproduction of acknowledged nuisance algal species [Reynolds 1998]. Favourable conditions of apposite temperature, adequate light, minimal turbulence and high nutrient concentration favour the increased growth of scum-forming cyanobacteria in surface waters. The control of buoyant cyanobacteria growth in reservoirs is of paramount importance to the water industry as these organisms produce toxins and compounds which taint the taste and odour of potable water.

Cyanobacteria blooms are prevalent during summer and early autumn in temperate and sub-tropical regions [Sivonen and Jones 1999]. During this period reservoirs are stratified, characterised by an upper stratum of homogeneous warm, circulating water, the epilimnion. The epilimnion overlies a relatively quiescent, deep and cool region, the hypolimnion. The region between the epilimnion and the hypolimnion is characterised by a sharp thermal discontinuity, and is known as the metalimnion [Monismith et al., 1990]. During stratification, the metalimnion minimises mass transfer and prevents surface induced mixing penetrating to the hypolimnion. Consequently the oxygen flux is restricted and the hypolimnion becomes anoxic due to chemical reduction processes and biological respiration. The epilimnion is relatively stable and ideal for increased algal and in particular buoyant cyanobacteria growth.

Individual water bodies have unique seasonal populations of cyanobacteria and eucaryotic micro-algae, dependent on meteorological and geochemical conditions. Excessive algal growth is likely to recur annually, in those water bodies that have a history of algal blooms, if there are minimal changes in the physical and chemical conditions [Sivonen and Jones 1999]. To control the abundance of scum-forming cyanobacteria and improve water quality, the physical and geochemical conditions can be altered within the water column. Thus, artificial destratification is often used to improve water quality [Stephens and Imberger 1993], and has been shown to reduce the growth of scum-forming cyanobacteria in reservoirs and lakes [Steinberg 1983; Visser et al., 1995; Steel and Duncan 1999].

Surface mixers have been installed at Happy Valley and Myponga Reservoirs, South Australia, complimenting the existing aerators, for destratification and control of cyanobacterial growth. The use of mechanical mixers for destratification is becoming increasingly popular; however, minimal research has been undertaken to determine the efficiency and impact of mechanical mixers. The obvious benefits include the range and flexibility of mixers available and economic savings. To destratify reservoirs large quantities of water need to be circulated, subsequently physically large surface mixers have been manufactured for Myponga and Happy Valley Reservoirs. The surface mixers (Figure 1) 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), via an 8-blade impeller with a diameter of 4.9 m. The blades have a pitch angle of 15° and the impeller rotates at 10 rpm. The flow through each surface mixer is approximately 3.5 m^3s^{-1}.

The chosen site for the analysis was Myponga reservoir (S 35° 24', E 138° 25'), Figure 2, situated ~70 km south of Adelaide on the Fleurieu peninsula, South Australia. Myponga reservoir is a highly managed water body with regular chemical ($CuSO4$) dosing to manage cyanobacteria growth, and prolonged artificial mixing. Myponga Reservoir is the primary water supply for the inhabitants of the Southern Fleurieu peninsula. The reservoir has a concrete arch-dam with a ski-jump spillway that was completed in 1962.

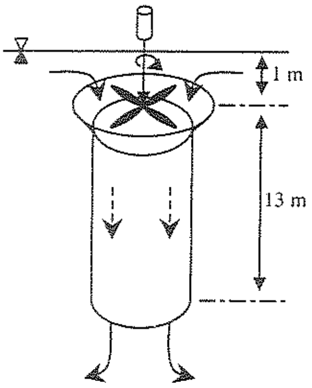

Figure 1. Schematic diagram of the surface mixers, arrows indicate the direction of flow.

The reservoir capacity is 26800 ML at a full supply level of 211.7 m A.H.D. (Australian Height Datum), an average depth of 15 m with a maximum depth of 36 m. The mean retention time based on abstraction is approximately 3 years. The surface area of the reservoir is 2.8 km^2 and the catchment area is 124 km^2. Water is removed from the reservoir via an off-take valve, located on he dam wall, at 195.2 m A.H.D. The multi-diffuser aerator is located adjacent to the dam wall at a depth of 30 m. The aerator diffuser has 160 outlets over a length of 200 m and air is delivered at 120 Ls^{-1} via a 100 kW compressor.

Data has been collected at Myponga for over two decades. In June 1999 two permanent meteorological monitoring stations were installed on Myponga reservoir that log meteorological data every 10 minutes. The meteorological station monitors:

- Temperature (°C) at discreet depths through the water column
- Wind speed (ms^{-1}) and direction (°)
- Relative humidity (%)
- Air temperature (°C)
- Incoming solar radiation (Wm^{-2})
- Net radiation between the water surface and atmosphere (Wm^{-2})

The surface mixers and aerator at Myponga reservoir are required to be operated continuously during the summer months. Therefore to fully analyse the effectiveness of the surface mixers numerical modelling has been undertaken.

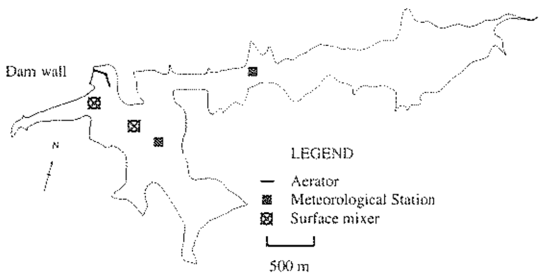

Figure 2. Myponga reservoir with locations of aerator, surface mixers and meteorological stations.

To simulate the physical behaviour of the reservoir the one-dimensional reservoir model DYRESM was used. The incorporation of a surface mixer algorithm into DYRESM required the following sequence of work to be undertaken:

- Develop an understanding of the flow field around the surface mixers, using ADV measurements and temperature profiling
- Develop an algorithm for the surface mixers for inclusion into DYRESM
- Use DYRESM to simulate Myponga reservoir, using existing aerator algorithm, and to validate the surface mixer algorithm
- Investigate the performance of aerator and surface mixer configurations

2. FIELD MEASUREMENTS

To determine an appropriate algorithm to model the operation of the surface mixers extensive flow profiling was carried out during stratified and isothermal conditions at Myponga reservoir. A field version Acoustic Doppler Velocimeter (ADV) with internal electronic compass and thermistor was suspended from a fixed mooring adjacent to the surface mixer located furthest from the dam wall (Figure 1) to measure the flow field. The ADV records 3-dimensional velocity reported in Cartesian coordinates.

Measurements were recorded at 50 Hz for 2-minute intervals every 500 mm through the water column. The process was repeated at numerous distances from the surface mixer ranging from 1 – 500m. The measurements were time-averaged using the 2-minute sampling time to ensure that the required draft tube radial, tangential and vertical flow was detected. Figure 3 shows the vertical and radial flow through the water column at 3.8 m from the centre of the surface mixer. Negative horizontal flow is radially away from the surface mixer and negative vertical velocity is downwards.

The profile was recorded on the 28/08/00, where a 2°C temperature difference existed between the surface mixed layer and the hypolimnion. The depth of the diurnal thermocline was ~1.5m. The flow exhibited upward swirling characteristics representing a swirling buoyant plume. A horizontal intrusion formed when the plume reached a level of neutral buoyancy at ~7m below the surface.

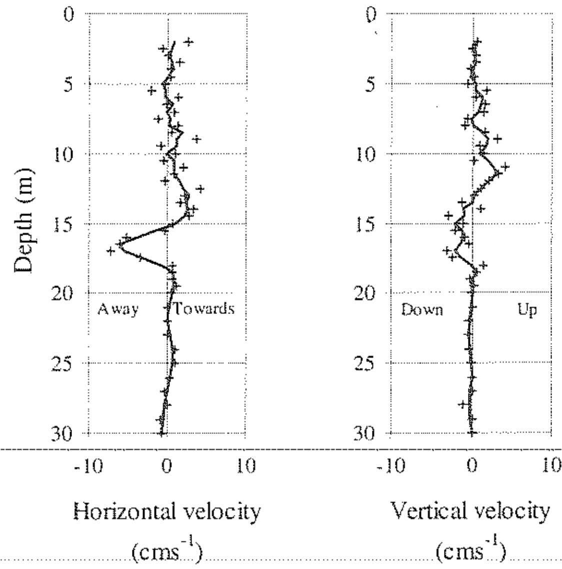

Figure 3. ADV measurements at 3.8 m from the centre of the surface mixer.

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 26/9/00 where a 4°C temperature difference existed between the surface and reservoir bottom. The depth to which the flow penetrated below the draft tube was ~1.8 m where no significant flow was detected, Figure 4. The propeller meter can measure flow accurately for angles ± 10°, and due to buoyancy and swirl, flow angles are not vertical. It is planned to use an ADV to measure the flow beneath the draft tube where the swirl characteristics can be quantified. The flow profile measured immediately at the draft tube exit shows a typical flow pattern downstream of an impeller.

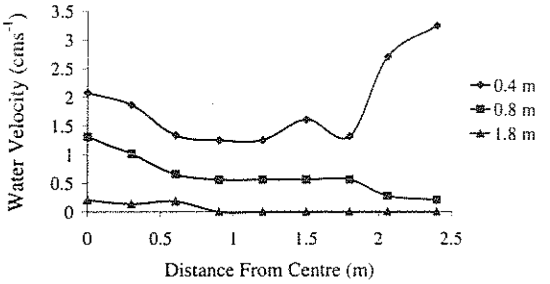

Figure 4. Averaged mean velocity, measured directly below the draft tube.

Temperature profiling recorded on the 19/02/01 taken at regular intervals away from the surface mixer supported the plume hypothesis. Figure 5 shows the exiting flow from the draft tube forming a horizontal intrusion. The plots in Figure 5 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.

3. 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. πD 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^3T^{-3}) of the plume is defined by

$$B = g\left(\Delta\rho_0 / \rho\right) Q_P (\pi D)^{-1} \tag{1}$$

in which $\Delta\rho_0$ 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^3T^{-1}), used is based predominantly on the comprehensive experimental investigation of Kotsovinos and List [1977] and is given by

$$Q_P = 3.32\left(\alpha / 2\right) z \sqrt[3]{B} (\pi D) \tag{2}$$

where z is the depth and α is the entrainment coefficient for plane plumes (0.083) [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].

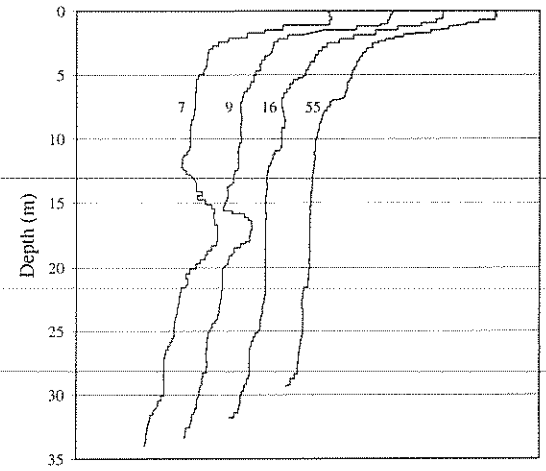

Figure 5. Temperature profiles taken on 19/02/01, from left to right recorded at 7, 9, 16 and 55 m from the surface mixer. The surface temperature was 24.5°C and the bottom temperature was 21.8°C.

The algorithm uses the following assumptions:

1. No initial momentum exists in the surface water entering the surface mixer.
2. The available impeller energy is always able to pump the surface water down to the outlet of the draft tube.

3. The flow exiting the draft tube has no jet characteristics
4. The attributes of the internal draft tube flow are the same as the surface water.

4. SIMULATION RESULTS

Myponga reservoir was simulated from September 1999 to September 2000 using hourly averaged meteorological data generating a daily output at midday. During January 2000 permanent stratification existed at Myponga reservoir for a period of two weeks and the threat of excessive cyanobacteria growth existed. The need for the surface mixers to have an impact is paramount during this period. A comparison of the measured temperature profile to the simulated data taken at 1200 midday on the 18/01/00 is shown in Figure 6. The measured temperature profile was taken from the meteorological station nearest the dam wall, where the reservoir is at its deepest (36 m).

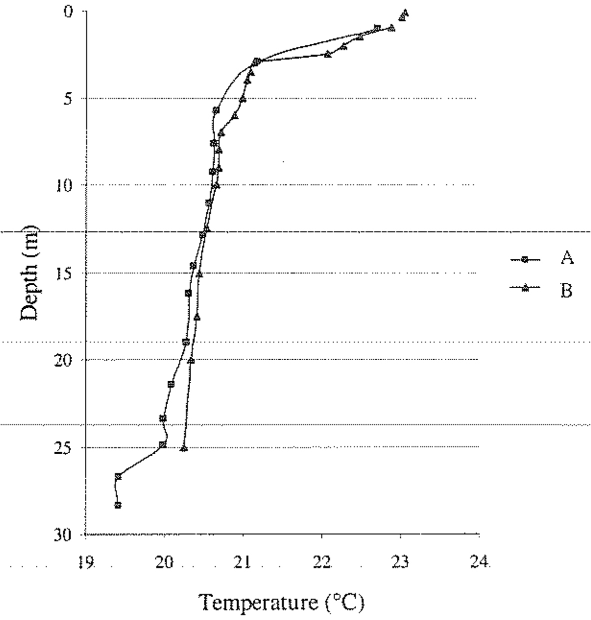

Figure 6. Simulated (A), using the aerator and surface mixer algorithms, and observed (B) temperature profiles for Myponga reservoir at midday 18/01/00, under artificially mixed conditions.

The simulation adequately modelled the temperature structure in the modelled period. The example shown in Figure 6 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. 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. Figure 7 shows the results from the following operational strategies:

1. No artificial mixing
2. Two surface mixers
3. Single aerator
4. Twenty-five surface mixers (same power consumption as the aerator)

Initially the model was run to determine the physical structure of the reservoir without the use of an aerator or the surface mixers. Under no artificial mixing excessive surface heating and permanent stratification occurred during the summer months. The profile in Figure 7 shows the surface mixed layer at a depth of ~3.5 m with a surface temperature of 25.4°C. A strong thermocline is evident at ~15 m. The hypolimnion is significantly cooler at 15.8°C. These conditions would be ideal for buoyant cyanobacterial growth.

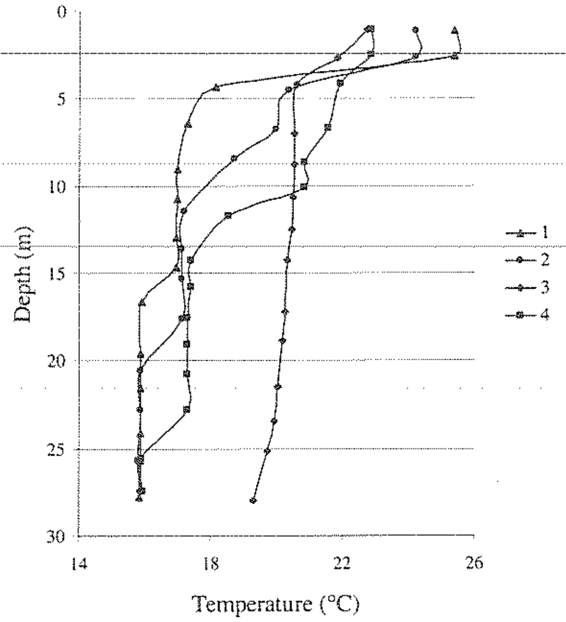

Figure 7. Simulated temperature profiles under the following conditions: (1) no artificial mixing; (2) two surface mixers; (3) single aerator; (4) Twenty-five surface mixers.

When the two surface mixers where implemented in the code the surface temperature dropped by more than 1°C and the thermocline was weakened. Slight deepening of the surface mixed layer is evident. The action of the two surface mixers impact the epilimnion directly as is seen between depths 4.5 and 11.5 m.

The aerator operated individually has a significant impact on the thermal structure. The water body below 4 m is well mixed and the temperature difference between the surface and the hypolimnion is dramatically reduced to 3.5°C. The surface mixed layer is relatively shallow (~3m). Historical data has shown that the aerator at Myponga adequately maintains aerobic conditions but has had minimal impact of the algal biomass.

The use of the surface mixers is to impact the surface mixed layer directly and remove buoyant cyanobacteria from the light. As seen, the use of two surface mixers does have a modest impact. When used in combination with the aerator the surface mixed layer is approximately 1 m deeper than when the aerator is used alone. The final plot in Figure 7 shows the physical structure at Myponga when twenty-five surface mixers are used. The surface mixed layer is considerably increased and the surface temperature is similar to when the aerator is used alone.

5. CONCLUSIONS

The surface mixer algorithm has been successfully incorporated into DYRESM and validated against Myponga reservoir field data. This study has shown that artificial mixing via surface mixers has a significant effect upon the thermal structure of a water body. The two surface mixers at Myponga do have an impact of the surface mixed layer, as is their intention, and modelling shows that using a larger number of surface mixers will increase the surface mixed layer considerably.

The combined use of aerators and surface mixers to manage water quality has great potential and deserves further investigation. Each water body is unique and numerical modelling can greatly assist in the planning and design of an appropriate destratification system. The investigation of the surface mixer impact on cyanobacteria growth has not been discussed here in any detail but is currently being investigated with numerical modelling using DYRESM-CAEDYM (aquatic ecological model) and field observations.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Fischer, H. B., E. J. List, R. C. Y. Koh, J. Imberger and N. H. Brooks, *Mixing in Inland and Coastal Waters*, Academic Press, 1979.

Kotsovinos, N. E. and E. J. List, Plane turbulent jet analysis. Part 1. Integral properties, *Journal of Fluid Mechanics* 81, 25-44, 1977.

Monismith, S. G., J. Imberger and M. L. Morison, Convective motions in the sidearm of a small reservoir, *Limnology and Oceanography* 35, 1676-1702, 1990.

Reynolds, C. S., What factors influence the species composition of phytoplankton in lakes of different trophic status, *Hydrobiologia*, 369/370, 11-26, 1998.

Sivonen, K. and G. Jones, *Cyanobacterial Toxins*. In: *Toxic Cyanobacteria in Water*, Chorus, I. and J. Bartram (eds.) 41-111, E & F N Spon, London, 1999.

Steel, J. A. and A. Duncan, Modelling the ecological aspects of bankside reservoirs and implications for management, *Hydrobiologia* 395/396, 133-147, 1999.

Steinberg, C., Effects of artificial destratification on phytoplankton populations in a small lake, *Journal of Plankton Research* 5, 855-864 1983.

Stephens, R., and J. Imberger, Reservoir destratification via mechanical mixers, *Journal of hydraulic engineering*, 119, 438-457, 1993.

Visser, P. M., H. A. M. Ketelaars and R. M. Luuc, Reduced growth of the cyanobacterium Microcystis in an artificially mixed lake and reservoir, *Water Science and Technology* 32, 53-54, 1995.