Assessment and analysis of Googong Reservoir thermistor chain data March - November 2007
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Cover Photograph: WEARS mixer at Googong Dam

Photographer: Chris Drury
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EXECUTIVE SUMMARY

Thermistor chain data collected by ActewAGL at three locations within Googong Reservoir have been checked for quality and analysed in terms of surface mixed layer dynamics and internal wave activity. The period of record for the data corresponds with a period during which a WEARS reservoir mixing system was operated.

The thermistor chain data are sound with all thermistors performing within the manufacturer's specifications. The data are in satisfactory agreement with water temperature data collected concurrently and independently by CSIRO.

The surface mixed layer depth during spring and early summer fell typically in the range of 3 - 8 m with the deeper mixed layer depths corresponding to periods of sustained south-to-southeasterly winds in excess of 4 m s$^{-1}$. The increase in mixed layer depth most likely reflects tilting of the thermocline rather than a uniform deepening across the entire reservoir through wind stirring. Possible consequences of such wind-induced motions are upwelling of hypolimnetic water at the southern end of the storage and a shallow surface layer. Inflows to the reservoir occur at the southern end as well. Conditions for algal growth are likely to be most favourable at the southern end of the reservoir because the expected shallower surface layer allows greater availability of light combined with increased availability of nutrients supplied (potentially) by upwelling and inflows from the catchment.

Operation of the WEARS mixer system has had a profound effect on the thermal stratification. Comparisons with historical water quality profile data show that the mixers effectively transport heat downwards into the water column. The mixers have clearly transported dissolved oxygen downwards but it is not possible yet to determine whether or not the total amount of oxygen in the reservoir has increased or if the available oxygen has just been redistributed.

Internal wave activity in the storage consists mainly of small scale vertical displacements of the thermocline (0.3 -0.4 m) punctuated by occasional (once or twice a month) large displacements of 2-5 m produced by strong winds from the south to southeast. Such larger scale displacements could conceivably lead to 'dirty water' events in the treatment plant should hypolimnetic water with low dissolved oxygen and high iron and/or manganese concentrations occur within this distance of the intake level.

As this is the first season of operation of the mixer system it is highly recommended to maintain a relatively intensive water column profiling regime to provide a clear understanding of the mixers' impact on the oxygen dynamics (and related chemistry) of the reservoir.
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1. INTRODUCTION

ActewAGL installed a WEARS reservoir circulation system in March 2007 to assist the management of water quality in Googong Reservoir. At the same time, three thermistor chains were deployed along the northern end of the reservoir to monitor the impact of the mixing system on the thermal stratification of the reservoir.

CSIRO has been contracted to assess the quality of the thermistor chain data and to analyse these data to determine the temporal patterns of surface layer depth, provide a preliminary assessment of internal wave activity, and comment on the impact of the mixer system on the reservoir’s thermal stratification.

As part of an ongoing independently-funded AWWArf research project, CSIRO has deployed its own thermistor chain and meteorological station in the reservoir. Although outside the scope of this contract, some data from the CSIRO instrumentation are used to provide an independent check on the ActewAGL thermistor chain data and to provide a basis for mapping wind speeds measured on the shore to those observed above the water surface.

The report commences with a description of the site, instrumentation, the data set supplied to CSIRO for assessment and the methods used to determine surface mixed layer depth and internal wave activity. This is followed by an assessment of the thermistor chain data quality. Finally, the thermistor chain data are analysed and an assessment of surface mixed layer dynamics and internal wave activity is provided.
2. METHODS

2.1. Site description

Googong Dam is the largest of the Canberra water supply storages. It is located on the Queanbeyan River 8 km SSE of Queanbeyan, NSW (35° 25.2’ S, 149° 15.8’ E). When full (full storage level = 663 m AHD) it has a volume of 121 GL, an area of 710 ha, and a mean depth of 17 m (Ecwise Environmental, 2006). A meteorological station is located on the west bank of the dam on a spur located a bit south of the dam. The dam has experienced occasional blue-green algal blooms and has been subject to routine water quality profiling for many years.

Since March 2007 the reservoir also has been instrumented with 3 thermistor chains by Ecwise and with a raft-mounted thermistor chain (TC) and meteorological station operated by CSIRO. The locations of all instrumentation are shown in Figure 1. Note that TC3 is located to the north, TC2 to the south with TC1 located in between.

A WEARS mixer system has been in operation at the reservoir since March 2007. The system consists of two pairs of counter-rotating impellers used to pumped surface layer water downwards through a 20 m long draft tube where it is released into the reservoir. The system has a nominal total flow rate of 24 m$^3$ s$^{-1}$. The intake to the pumps has an invert depth of ~ 1.5 m). Initially there were a few interruptions in the operation of the mixer (Elliot, pers. comm.) but since winter 2007 it has operated continuously.
Figure 1 Googong Reservoir instrument and sample site locations. Ecowise thermistor chains TC1 (410748WT1), TC2 (410748WT2), TC3 (410748WT3), meteorological station (570818), water quality sampling sites 717, 718 & 722. Also shown are the locations of the WEARS mixers and the CSIRO instrument raft. Note: only the northern 40% of the reservoir is shown.
2.2. Description of data set

Thermistor chain and meteorological data were provided by ActewAGL as delimited text files produced by interrogating a HYDSYS database. The thermistor internal data logger clocks were not synchronised prior to deployment and HYDSYS was used to either average or interpolate the individual time series to produce output on a consistent 15 minute time interval. The thermistor spacing and periods of record for each chain are listed in Table 1.

No information was provided regarding the sampling and logging intervals associated with the meteorological data.

Table 1 Googong Dam thermistor chain deployments.

<table>
<thead>
<tr>
<th>ID (this report)</th>
<th>ActewAGL ID</th>
<th>Depth range</th>
<th>Record start</th>
<th>Record end</th>
<th>Temperature range when mixed</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1</td>
<td>410748WT1</td>
<td>Every 1 m from 1-15 m, 18 m</td>
<td>7 Mar 2007 12:15</td>
<td>10 May 2007 11:45</td>
<td>0.12 °C</td>
<td></td>
</tr>
<tr>
<td>TC2</td>
<td>410748WT2</td>
<td>Every 1 m from 1-15 m, then every 3 m from 18 - 30 m</td>
<td>7 Mar 2007 15:15</td>
<td>22 Nov 2007 10:15</td>
<td>0.17 °C</td>
<td></td>
</tr>
<tr>
<td>TC3</td>
<td>410748WT3</td>
<td>Every 1 m from 1-15 m, then every 3 m from 18 - 45 m</td>
<td>7 Mar 2007 14:00</td>
<td>22 Nov 2007 09:45</td>
<td>0.21 °C</td>
<td>Missing record 2 - 6 July 2007 Data for 33 m and below is interpolated from 4 Apr 07 - 2 May 07</td>
</tr>
</tbody>
</table>

2.3. Instrumentation specifications

The ActewAGL thermistor chains are made of individual Onset TidbiT temperature sensors each with their own internal clock and data logger. The manufacturer's specifications for the ONSET TidbiT loggers are given in Table 2.

No information regarding the meteorological instrumentation was provided.

Table 2 Onset TidbiT temperature logger specifications

<table>
<thead>
<tr>
<th>Measurement Range</th>
<th>-20° C to 30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>± 0.2 °C from 0 °C to 50 °C</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.02 °C at 25 °C</td>
</tr>
<tr>
<td>Response time (90%)</td>
<td>300 s</td>
</tr>
</tbody>
</table>

The specified performance of the ActewAGL thermistor chains is different from the CSIRO thermistor chain. The CSIRO monitoring system using 10 minute averages of 10 second data using thermistors with a 1.2 s response time, an accuracy of ±0.015 °C and a resolution of 0.007 °C. The averaging performed by the CSIRO system filters out temperature fluctuations with a period shorter than 10 minutes. The TidbiT data will contain higher frequency fluctuations as the only filtering of high frequency fluctuations is due to the TidbiT's relatively slow response time of 5 minutes. The difference in performance between the two systems has the following implications with regards to the surface mixed layer depth and internal wave activity analyses presented elsewhere in this report.

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2.4. Mixed layer depth and isotherm depth calculations

The surface mixed layer depth is operationally defined as the depth at which the water temperature is 0.1 °C colder than the top thermistor (Sherman et al. 2000). This definition is based on analysis of many years of CSIRO water temperature monitoring data. The TidbiT resolution of 0.02 °C is satisfactory for this purpose. However, the 0.2 °C absolute accuracy may introduce an error in the determination of the surface layer depth should there be an offset in the relative calibrations of adjacent temperature loggers during periods of weak thermal stratification.

Isotherm depths are determined by specifying a temperature and then searching each thermistor chain time sample for the depth at which that temperature occurs. The search begins at the water surface and works downwards progressively through the thermistors until the specified isotherm temperature is bounded by adjacent thermistors. Linear interpolation is then used to compute the location of the isotherm between the bounding thermistors. In regions with weak thermal stratification, relative calibration offsets have the potential to introduce uncertainty in the determination of the isotherm depth.

To illustrate the possible error in isotherm depth, the 13 m thermistor at TC2 outputs temperatures about 0.05 °C colder than the thermistors as 12 and 14 m. There are circumstances where a search for, say, the 15° isotherm could fall between 12 and 15 m but the calibration offset ensures that the shallowest depth between 12 and 13 m will always be selected by the algorithm (Table 3). This error reflects both a relative calibration offset and possible contributions arising from the HYDSYS interpolation algorithm and the instantaneous nature of the TidbiT sampling which may allow some influence of higher frequency temperature fluctuations. Fortunately, such circumstances are rare and are not expected to impact substantially on the analysis presented in this report.

Table 3 Temperatures at TC2 on 21 Nov 2007 22:30:00.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 m</td>
<td>15.10</td>
</tr>
<tr>
<td>13 m</td>
<td>14.97</td>
</tr>
<tr>
<td>14 m</td>
<td>15.04</td>
</tr>
<tr>
<td>15 m</td>
<td>14.71</td>
</tr>
</tbody>
</table>
3. QUALITY CHECKING OF THERMISTOR CHAIN DATA

Inspection of the data showed that all thermistors performed within specification (absolute accuracy ± 0.2 °C). Relative offsets in individual calibrations were checked by comparing temperatures during a period of water column cooling leading to complete mixing of the water column. The difference between minimum and maximum recorded temperature is listed as the 'temperature range when mixed' in Table 1. The relative calibration offset between adjacent thermistors can impact on the automated determinations of both surface mixed layer depth and isotherm depths (section 2.4) presented in the analysis section of this report.

The complete records for all thermistor chains are plotted in Figures 12-25. All data appear sound with the following exceptions.

There appears to be a problem with TC2 data below 15 m from August 2007 onwards. The TC2 data suggest no appreciable thermal stratification below 15 m during spring 2007 (Figures 22-24) whereas TC3, the CSIRO thermistor chain (not shown) and ActewAGL profile data collected along the length of the storage all confirm that the stratification evident in the TC3 data is correct (Figure 2). This suggests the possibility that the thermistors below 15 m are suspended at the same depth. Perhaps they became tangled together at their last deployment.

The complete records for all thermistor chains are plotted in Figures 12-25. All data appear sound with the following exceptions.

Figure 2 Temperature profiles at TC2, TC3 and measured using a water quality profiler at water quality sites 717 and 722 on 19 Nov 2007.

TC3 data for depths 33 m and below are not valid prior to ca. 2 May 2007 (Figure 19). It appears that the temperature values provided for these thermistors have been linearly interpolated from 4 April through 2 May. It would be best to simply flag these values as no data.

The potential for uncertainty in the determination of surface mixed layer depth is illustrated in Figure 3 where at 0545 h the temperatures from warmest to coldest are in the following depth order: 4 m, 2 m, 5 m, 3 m, 1 m. If the data were absolutely correct they would imply a temperature distribution that is highly unlikely to occur in nature, especially when winds are light (0.7 m s⁻¹) such that penetrative convection (heat loss from the water surface to the
atmosphere) is the dominant source of mixing energy. All of the temperatures are within approximately 0.1 °C of one another – so they are all clearly performing within specification – but the relative changes in temperature make automated determination of surface layer depth much more difficult and less accurate.

It is possible to compensate for relative calibration offsets by performing a calibration on all temperature loggers on a single chain to determine the offset that should be applied. There are two approaches that may be used:

- The best option is to perform the calibration under controlled conditions in a laboratory using a temperature bath and a reference temperature standard.
- It is also possible to deduce corrections by performing a quasi-calibration in situ. In this case the temperatures of all temperature loggers should be compared at a time when the entire water column is known to be mixed and therefore isothermal. Typically, this can only be done with confidence during early winter when the water column is still losing heat (Figure 4) and care must be taken to make sure that cold underflowing currents are not present (only the deepest temperature loggers are likely to be effected, e.g. Figure 5) which may produce a subtle temperature change that could be mistaken for a calibration offset.

![Figure 3 Temperature traces at AGLTC2 (410748WT2) during the morning of 8 Mar 2007. The relative temperatures during the period 0500-0600 exhibit signs of a relative calibration offset.](image1)

![Figure 4 Temperature traces at AGLTC2 (410748WT2) during autumnal cooling of the well-mixed water column. All temperatures in the top 7 m of the water column are within a ± 0.2 °C band.](image2)
Figure 5 Temperature traces at AGLTC2 (410748WT2) during the coldest period of winter 2007. Evidence of cold intrusions is evident in the temperature traces at 24, 27 and 30 m on 26 and 27 July.
4. ANALYSIS

4.1. Seasonal stratification pattern

The surface layer temperature ranged from a maximum of 23-24 °C in March 2007 (Figures 17-19) to a winter minimum of about 7 °C in late July 2007 (Figures 22-23). During spring the surface temperature rose back to 23 °C by late November (Figures 24-25).

Clear evidence of the impact of the mixers is evident in the sudden increase in temperatures below 9 m during late March through early May 2007 and in the cooling of temperatures above 9 m depth during late March when the water column was cooling from the surface while at the same time the temperature gradient from 5-7 m intensified (Figure 19). On 16 March 2007 there was no appreciable temperature difference from the surface to 7 m depth. From 16 to 19 March the temperature difference between 3 and 7 m actually increased before autumnal cooling eventually deepened the surface layer back down to 7 m on 25 March. The mixer was effectively relocating surface layer water to below 10 m which in turn displaced the overlying relatively colder water upwards thereby producing the decrease in water temperature seen in the thermistors at 4, 5, 6 and 7 m depth.

The impact of the mixers can also be seen in the nearly linear increase in temperature with time of all thermistors, including the deepest ones, during September and October 2007. The water temperature below 14 m is seen to have warmed to levels above the natural (pre-mixer) condition by comparing temperatures during spring 2007 (Figure 25) to those observed at the same depths in March 2007 (Figure 19). Very effective deep circulation is required to produce such an increase in water temperatures below 14 m. Without the enhanced circulation, the water column would be expected to warm only at the surface during spring and summer with very much less downwards transport of heat due to turbulent diffusion.

4.2. Surface mixed layer dynamics

The depth of the surface mixed layer was determined from the thermistor chain data as the depth at which the temperature was at least 0.1 °C colder than the 1 m deep thermistor. The maximum depth of the surface layer typically occurs just before sunrise when nighttime cooling has had its maximum mixing effect and before the onset of diurnal stratification. The maximum daily surface mixed layer depth is the depth to which buoyant phytoplankton that occupy the surface layer are redistributed before photosynthesis begins when the sun comes up. If the mixed layer depth is more than 3 times the euphotic depth (1% light transmission) then conditions are not suitable for the common forms of nuisance blue-green algae to grow (Sherman et al. 1998).

The maximum daily surface mixed layer (SML) depth for the entire period of record is shown in Figure 6. The SML deepens slightly during early autumn (7 Mar - 20 Apr) with a median depth of roughly 7 m. Differences in Z_m of ±1 m are within the tolerance of the calculation method and should not be interpreted as demonstrating a spatial trend given the relative calibration offsets of the temperature loggers. The maximum depth during winter is simply the depth of the deepest thermistor on each chain. Rapid cooling occurs from late Apr to late May and the water column appears to have been completely mixed by 20 May.

The reservoir remained completely mixed throughout winter with the exception of a brief period during 20 Jun - 7 Jul when temperatures at the deeper thermistors (> 21 m) at TC2 and TC3 dropped more rapidly than did the overlying thermistors. This was a period with either calm winds and freezing temperatures or periods of rain and cold temperatures (4 - 6 °C). Both weather conditions can produce cold currents that flow along the bottom of the reservoir. In the first case, heat losses from shallow areas can cause cold gravity currents to form and descend to the bottom of the water column in a process known as 'differential
cooling’ (Wells and Sherman 2001). In the latter case, cold river inflows simply propagate along the bottom of the reservoir. Both processes can produce thermal stratification at the bottom of the water column through the insertion of cold water.

Warming of the water column commenced at the beginning of August (Figures 22-23) but persistent thermal stratification did not commence until mid-August when a surface layer of roughly 20 m depth formed. From early September through late October the surface layer became progressively shallower shoaling from 15 m to roughly 3 m. During November the surface layer varied from 3 m to 8 m deep depending on weather conditions. CSIRO data (Figure 7) confirms the results from the ActewAGL thermistor chains. The CSIRO data confirms (not shown) that the surface layer remained in the 3 - 8 m depth range through 8 Feb 2008.

![Googong Reservoir Surface Layer Depth](image1)

**Figure 6** Daily maximum surface mixed layer depths derived from thermistor chain data in Googong Reservoir 7 Mar 07 - 22 Nov 07.

![Googong Reservoir Surface Layer Depth](image2)

**Figure 7** Comparison between daily maximum surface mixed layer depths derived from ActewAGL TC2 and TC3 and the CSIRO thermistor chain data.

During summer the surface layer remains in the range of 3 to 8 m with the deeper excursions corresponding to periods of sustained southerly winds. For example, during 5-10 Nov 07, the surface layer was 8 m deep (Figure 7) due to sustained south to southeasterly winds of 4-8 m s\(^{-1}\) (Figure 8). Such strong winds will produce internal waves (section 4.3) that cause the thermocline to tilt downwards at the downwind end producing an 'apparent' deepening of the surface layer. It is likely during such periods that upwelling (or at least surface layer shoaling) occurs at the upwind end of the reservoir as has been observed in Hume Dam during periods of sustained winds (Sherman 2003).

Summer surface layer conditions are likely to be more conducive to algal bloom formation at the southern end of the storage. A shallower surface layer depth would provide greater light
availability. Upwelling potentially could introduce nutrients released from the sediments (if any) into the surface layer at the southern end as well. Finally, the southern end is where most inflows enter the reservoir. These inflows may also introduce significant amounts of nutrients to the water column.

Figure 8 Wind speed and direction measured at ActewAGL meteorological station at Googong Dam 22 Oct - 22 Nov 2007.

4.3. Internal wave activity

Internal wave activity was assessed by plotting the depth of an isotherm and observing its vertical displacement over time. This displacement is the distance that water is moving up and down through the water column. In reservoirs where low dissolved oxygen and high iron and manganese concentrations correlate with thermal stratification (a common condition) this displacement may be associated with the occurrence of ‘dirty water’ events at treatment plants when the displacement is sufficient to lift dirty water into the intake of the treatment plant.

Figure 9 shows the internal wave activity during March 2007 under natural conditions before the mixers were turned on (prior to 16 Mar 07) and during their operation afterwards. There was relatively little vertical motion; the RMS displacement of the 11 °C isotherm through 17 Mar was 0.41 m and for the 18 °C isotherm it was 0.29 m. Extremely windy conditions produced a very rapid response throughout the water column late on 24 Mar with vertical displacements ranging from 2 to 5 m but rebounding back to previous levels after a few hours.
Figure 9 Internal wave activity (isotherm displacements) and wind speed at Googong Reservoir during March 2007.

The displacement of the 17 °C isotherm during 14-22 Nov is shown in Figure 10 for ActewAGL TC2 and TC3 and the CSIRO thermistor chain (located close to TC3). Calculations of the isotherm depth at TC3 and the CSIRO thermistor chain gave very similar results whereas the isotherm depth at TC2, located further south along the long axis of the storage was typically shallower. Rapid displacements of approximately 2 m occurred in response to brief but strong south and southeasterly winds (> 6 m s⁻¹) during the afternoons of 17, 18 and 19 Nov. Moderate NW winds around midday on 17 Nov caused the isotherm to rise at TC3 to above the level at TC2 as the wind caused the thermocline to downwell at the southern end of the reservoir. Because TC2 is located closer to the centre of the long axis of the reservoir the displacements experienced there have a smaller amplitude than observed at TC3 near the north end of the storage.

The dominant periods of the internal waves were computed for the 17°C isotherm during 15-20 Nov 2007 after detrending the data for any constant trends due to heating or cooling. A fast Fourier transform was applied to the resultant time series to determine the dominant periods of oscillation. The most significant activity occurs with periods of 24, 12 and 8.2 h (Figure 11). Both wind speed and direction have a strong periodicity of 12 h and this most likely is the main source of energy that excites the internal wave activity in the reservoir.
Figure 10 Displacement of the 17°C isotherm and corresponding wind speed and direction 15-21 Nov 2007.
Figure 11 Power spectra for the displacement of the 17 °C isotherm (top), wind speed (middle), and wind direction (bottom). The analysis was applied to a 5.3 day period of record commencing 15 Nov 07 at 04:30.
5. IMPACT OF WEARS MIXERS ON THERMAL STRATIFICATION

5.1. The nature of mixer-induced circulation in reservoirs

Operation of the mixer creates a flow pattern that can be visualised as an upside down mushroom cap at the exit of the draft tube. The flow then rises around the draft tube because the surface layer water that has been transported downwards is warmer than the temperature at the draft tube exit. As the water rises it entrains ambient fluid from the water column and the temperature of the flow decreases due to this entrainment. Eventually the temperature in the circulator flow matches that in the surrounding water column and an intrusion forms which carries the mixer flow horizontally away from the draft tube at this level of neutral buoyancy. As the temperature difference between the surface layer and the bottom of the draft tube decreases, the momentum of the jet is able to propagate further downwards so that colder water may be entrained and the level of the intrusion will deepen with time provided the surface layer continues to cool.

As the intrusion propagates away from the mixers it eventually reaches the thermistor chains and the temperature for a thermistor in the intrusion zone begins to rise as the intrusion inserts itself into the overall water column at this depth. Conservation of mass requires that water from above intrusion is being relocated from the water column at the flow rate through the mixers and water from below the intrusion is being removed due to entrainment as the mixer flow rises along the draft tube. This circulation pattern can be expected to produce an apparent cooling above the intrusion as cooler water is drawn upwards to replace the water pumped down by the mixer.

The expected mixer-induced cooling behaviour above the intrusion would be relatively small and unlikely to be detected in thermistor chain data because the large surface area of the storage ensures a relatively thin net vertical displacement on a daily basis. The thermal effect of this displacement is compensated for by the strong heating of the water column and downwards diffusive flux of heat through the water column which are expected to dominate the temperature stratification in the upper water column.

Below the intrusion the situation is quite different as this is typically below the euphotic zone and solar heating is negligible. In this case changes in temperature arise through the downwards vertical diffusion of heat and the lateral flow of heat through the intrusion. The intrusive heat flux is much larger than the diffusive flux and so the effect of the mixer flow is prominent in the deeper thermistor chain data.

Because the temperature of the surface layer varies diurnally, it seems likely that the mixer flow will have a diurnally varying temperature as well. This implies that the level of neutral buoyancy at which the intrusion spreads out laterally will vary diurnally as well. However, the amount of this variation may be small in comparison to the natural vertical displacement in the water column due to wind-driven internal wave activity.

5.2. Observations of the impact of mixer operation on the stratification in Googong Dam

The operation of the WEARS mixers is evident in all of the thermistor chain data from 16 Mar 07 onwards and is seen as the progressive increase in temperature at depths from 10 m and below. Figure 12 compares the temperatures at 15 m and 18 m depth for all three thermistor chains.

As the surface layer cools, the mixer jet propagates deeper into the water column and the intrusion forms at progressively lower depths. This is seen in the figure as the temperature at 15 m warming sharply beginning on 19 Mar 07 and then stabilising on roughly the 26 Mar 07. The bottom of the intrusion continues to deepen and on 26 Mar 07 the temperature at 18 m begins its sharp increase and approaching the temperature at 15 m during the first week in April.
An interesting feature of Figure 12 is that the temperature increase at TC3 consistently leads that at TC1 and TC2 which appear to respond in unison with one another. Comparisons of thermistor chain data (not shown) revealed that the temperature between 5 and 15 m at TC3 was consistently warmer than that at TC1 and TC2 from 17 Mar 07 until temperatures converged in April. This implies that the intrusion is thicker north of the mixers as compared to south of the mixers. This may reflect the influence of the northern boundary of the storage on the propagation of the intrusion, i.e. the intrusion will strike the northern boundary much sooner than the southern boundary. If we assume the mass flux moving away from the mixer (but in the vicinity of the mixer) does not depend strongly on direction then the intrusion will have to expand more rapidly in the vertical at TC3 to accommodate the mass flux than would be the case for the thermistor chains south of the mixers. This implies a relatively larger return flow below the intrusion north of the mixers.

Figure 12 Temperature traces at 15 m and 18 m depth for the three thermistor chains show the influence of the mixer during the early autumnal cooling phase in late March 2007.

5.3. Impact of mixers on stratification - comparison with historical data

The impact of the WEARS mixer on the development of thermal stratification is evident in Figures 13-16. The mixers have been very effective at pumping heat downwards with the temperature at 15 m depth normally 11-12 °C in early December having increased to about 16-17 °C at an equivalent time in December 2007. The thermocline and oxycline are strongest between 6 and 12 m depth during normal (no mixer) conditions in 2006 whereas the sharp gradients are replaced by a more continuous gradients from 6 to 25 m due to the impact of the WEARS mixers.

The situation differs somewhat for the case of dissolved oxygen. Early in the development of stratification, i.e. up through November, the mixers have transported enough dissolved oxygen downwards to raise the concentration at 15 m depth from 6 to 7 mg L⁻¹. However, after another month of operation the dissolved oxygen is similar at 15 m depth for both years but is appreciably less during 2007 above a depth of 9 m at site 717 (Figure 14). At site 722 it appears that the oxygen content of the water column has increased overall.

It would be wise to compute a reservoir oxygen mass balance to establish whether the total amount of oxygen in the reservoir has been increased through the action of the mixers or if they have only redistributed the available oxygen throughout the water column. Note that when dissolved oxygen profiles from site 722 are overlaid (not shown) on those of site 717 they reveal similar concentrations at both sites, i.e. there appears to be relatively little horizontal variability in dissolved oxygen between the two sites. Calculation of an oxygen mass balance is beyond the scope of this report.
Possible consequences of mixer operation include that by increasing the temperature over much of the water column and at the sediment-water interface in shallower regions (say < 25 m) there may be an increase in the sediment and water column oxygen demands. The significance of such an effect will depend on the amount of organic matter available to fuel microbial activity.

5.4. Implications of mixer operation for early warning of dirty water events

A possible consequence of mixer operation is that previous experiences relating water temperature to the occurrence of dirty water events may no longer be applicable. Dirty water events occur typically when internal wave activity causes an upwelling of the thermocline in the vicinity of the reservoir’s offtake. Hypolimnetic water with low dissolved oxygen and high reduced Fe and/or Mn rises into the offtake’s withdrawal layer which is subsequently drawn into the water treatment plant causing a rapid deterioration in raw water quality.

It is not uncommon for operators to be able to correlate dirty water events with water column temperature. For example, Figures 15-16 indicate that prior to implementation of the WEARS mixer system an 11 °C isotherm could be expected to correlate well with dissolved oxygen concentration < 4 mg L⁻¹. Assuming this isotherm also correlated well with high Fe or Mn then the operators could in principle use real-time thermistor chain data to anticipate a dirty water event, i.e. if the temperature at the level of the offtake began to decrease it might be possible to extrapolate to a time when the 11 °C isotherm was likely to arrive and prepare for the arrival of dirty water.

The mixer system will change the nature of the underlying relationship between water temperature, dissolved oxygen concentration and the concentrations of Fe and Mn. Operation of the mixer produces a steady increase in temperature during spring and early summer whereas previously one could confidently expect water temperature at depth to vary much more slowly over time. The mixer has also caused a significant redistribution of oxygen within the water column. The change in thermal stratification means that previous relationships between temperature and dissolved oxygen probably will no longer apply and that in the future the correlation between temperature and dissolved oxygen may become more variable. Predicting the impact of the changes in dissolved oxygen on Fe and Mn is not within the scope of this report and it is recommended that this be monitored closely. The impact of a warmer hypolimnion on oxygen demand, nutrient release and metal chemistry also should be examined.

There is no a priori reason excluding the possibility of developing a predictive capacity for dirty water events. However, changes in the operation of the reservoir mean that previous relationships may no longer hold and requires that the temperature and chemistry of the reservoir be studied closely to establish what the new relationships between these parameters will be as a consequence of the use of the mixer system. It could be the case that operation of the mixers changes the chemistry in such a way that dirty water events become less (or more) of a problem.
Figure 13 Evolution of thermal stratification at site 717 during spring 2006 (no mixers) (a), and spring 2007 (WEARS mixers operating) (b). Date format is yymmdd.

Figure 14 Evolution of dissolved oxygen stratification at site 717 during spring 2006 (no mixers) (a), and spring 2007 (WEARS mixers operating) (b). Date format is yymmddd.
Figure 15 Evolution of thermal stratification at site 722 during spring 2006 (no mixers) (a), and spring 2007 (WEARS mixers operating) (b).

Figure 16 Evolution of dissolved oxygen stratification at site 722 during spring 2006 (no mixers) (a), and spring 2007 (WEARS mixers operating) (b).
6. CONCLUSION

The thermistor chains deployed by ActewAGL in Googong Reservoir are performing within specifications and clearly demonstrate the profound effect of the WEARS mixer system on the thermal stratification of the water column. The mixers have had no appreciable impact on the depth of the surface mixed layer during spring and summer - it persists at 3-8 m deep. However, by weakening the overall temperature gradient it is reasonable to expect that autumnal deepening and eventual overturn of the water column may be brought forward in time by several weeks or more. This could have the effect of shortening the potential cyanobacterial bloom season (should one exist) by inducing light limitation earlier in the year over the northern end of the reservoir.

Operation of the mixers causes very substantial warming of the hypolimnion. It is not yet possible to say what the consequences of this change will be on in situ oxygen demand and the potential for nutrient, Fe and Mn release from the sediments will be, but they may be profound as microbial processes accelerate rapidly in response to rising temperatures.

Operation of the mixers means that previous relationships that may have been established between temperature, dissolved oxygen and reduced species of Fe and Mn almost certainly no longer hold. If early warning of dirty water events based on these relationships is desired, it will be necessary to study the chemistry of the reservoir closely during the first few years of operation of the mixers in order to determine how these relationships have changed.
7. REFERENCES


8. APPENDIX 1 - TEMPERATURE DATA

Figure 17 Water temperature measured at TC1 (410748WT1) 3 Mar 07 - 10 May 07.
Figure 18 Water temperature measured at TC2 (410748WT2) 7 Mar 07 - 30 Apr 07.
Figure 19 Water temperature measured at TC3 (410748WT3) 7 Mar 07 - 30 Apr 07.
Figure 20 Water temperature measured at TC2 (410748WT2) 1 May 07 - 30 Jun 07.
Figure 21 Water temperature measured at TC3 (410748WT3) 1 May 07 - 30 Jun 07.
Figure 22 Water temperature measured at TC2 (410748WT2) 1 Jul 07 - 31 Aug 07.
Figure 23 Water temperature measured at TC3 (410748WT3) 1 Jul 07 - 31 Aug 07.
Figure 24 Water temperature measured at TC2 (410748WT2) 1 Sep 07 - 21 Nov 07.
Figure 25 Water temperature measured at TC3 (410748WT3) 1 Sep 07 - 21 Nov 07.