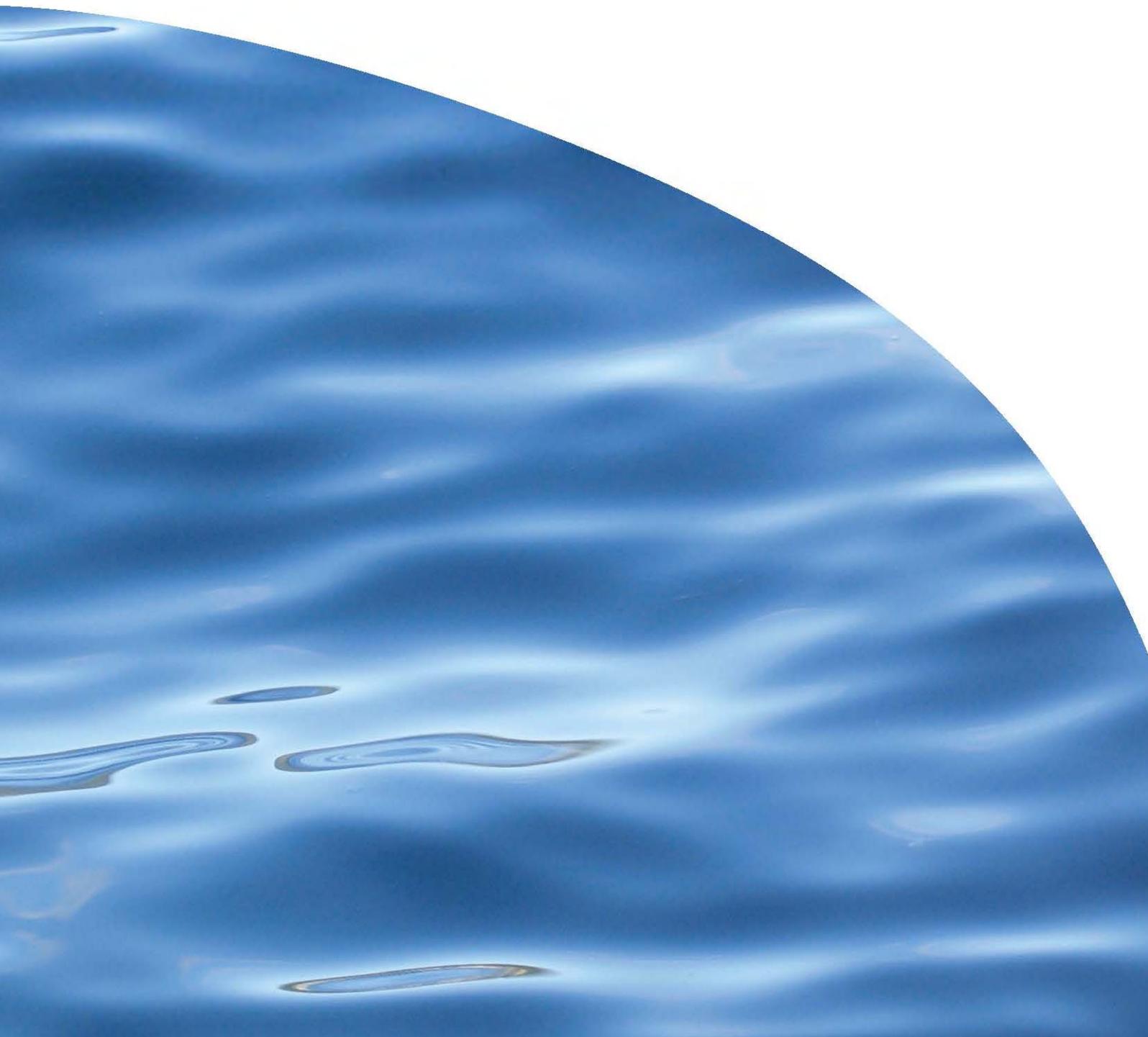


REPORT NO. 2720

**FEASIBILITY ASSESSMENT FOR
DESTRATIFICATION MIXING AND HYPOLIMNETIC
AERATION IN THE MAITAI RESERVOIR**



FEASIBILITY ASSESSMENT FOR DESTRATIFICATION MIXING AND HYPOLIMNETIC AERATION IN THE MAITAI RESERVOIR

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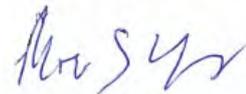
Prepared for Nelson City Council

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EXECUTIVE SUMMARY

Operations of the Maitai water supply scheme in the Upper Maitai Catchment have the potential to affect the ecological health of the Maitai River further downstream through their effects on flow regime, water temperature, and water quality. Since the reservoir's construction, there has been a consistent pattern of mid- to late-summer anoxia in the reservoir bottom waters owing to seasonal thermal stratification, which extends from October through April. Anoxia is highly undesirable because it results in poor habitat conditions for aquatic life in the reservoir. Anoxia also promotes biogeochemical cycling processes that produce harmful contaminants such as dissolved metals (principally manganese and iron), sulphides, and solubilisation of metal-oxide bound nutrients. Previous investigations have suggested mitigation measures such as reservoir destratification or aeration of the hypolimnion could potentially rectify these water quality problems, thereby improving the quality of water discharged to the Maitai River.

This investigation analysed a two-year monitoring record of stratification and deoxygenation cycles in the Maitai Reservoir, and explores three options for reversing hypolimnetic anoxia-associated water quality problems. These options include:

1. destratification of the reservoir through aeration mixing
2. hypolimnetic aeration through compressed air injection
3. hypolimnetic water transfer (pumping) using aerated surface waters.

Based on deoxygenation patterns observed over 2013–2015, analyses suggest reservoir destratification using aeration mixing, is a viable option for mixing and reoxygenating the reservoir during periods of low oxygen. Based on information provided by an external engineering consultant, an appropriately-sized destratification device would consist of a 15 kw compressor supplying approximately 30 l/s of compressed air through a 165 m perforated sparge line anchored near the bottom of the reservoir along its main basin. Using this approach, destratification and reoxygenation of the reservoir is predicted to be achievable within 10–14 days. Continuous or intermittent operation of the device could be considered over the stratification period, with the key time period for operation being between December and April. The total cost of the design and installation of the device is estimated at \$1,049,000 with annual operational costs of \$20k per annum (if operated continuously over seven months) or \$9k per annum if operated intermittently.

Analysis of total oxygen consumption rates in the reservoir hypolimnion indicate that hypolimnetic aeration could also be a viable option for reversing deoxygenation in the reservoir. Based on deoxygenation patterns observed over 2013 / 15, and aerating the hypolimnion to maintain dissolved oxygen concentrations in excess of 5 mg/L, air injection would need to occur at an average rate of between 4.6-7.1 l/s. However exact injection rates would depend on the oxygen transfer efficiency of the diffuser manifold, which is presently unknown. Between 3 to 7 separate diffuser manifolds distributed across the reservoir basin may be required, but this would depend on the design of the manifolds and horizontal current

patterns in the hypolimnion, which are presently unknown. The total cost of the design and installation of the device is estimated at \$915,000 with total operating (power) and maintenance estimated to be \$7k per annum if operated continuously over six months.

Preliminary investigations have been undertaken into the feasibility of reversing deoxygenation by piping oxygenated river water from the North Branch tributary to the reservoir hypolimnion. Based on total hypolimnetic oxygen consumption rates, on average 129 l/s of river water would need to be piped to the hypolimnion to a depth of around 20 m to offset deoxygenation. The North Branch tributary has a 7-d mean annual low flow of 89 l/s, so flow requirements would, at times, exceed available flows in the North Branch tributary. Such a large diversion would likely have pronounced environmental effects in the river, and a requirement for diversion in the summer period would compound these issues. Given the use of aerated surface waters would require a substantial diversion of flow, it appears unlikely to be a viable option.

Overall, either destratification or hypolimnetic aeration devices could feasibly improve water quality in the Maitai Reservoir. Both options can be designed to address the extent and rate of deoxygenation, and be scaled to a reservoir's morphometry (*i.e.*, area, depth, shape). A distinct advantage of hypolimnetic aeration over destratification would be that it would preserve the cool-water habitat in the reservoir hypolimnion. This could allow release of cooler water to the Maitai River during sensitive periods. It is probable that a destratified (mixed) reservoir could generally maintain water temperatures within the current consented limits (*i.e.* < 3 °C change, and < 20 °C) downstream of the Maitai River backfeed; however, it would give less flexibility. There is presently no New Zealand expertise and engineering experience in hypolimnetic aeration, therefore this would need to be sought from overseas. Destratification devices are likely to be more easily accessed, and are presently in operation at several reservoirs within New Zealand (*e.g.* Watercare, Opuha Dam Company).

Costs associated with either destratification or hypolimnetic aeration are likely to be similar. Both require the construction of compressor and air-transfer systems to a reasonable extent of the reservoir basin. There was greater uncertainty around costs for hypolimnetic aeration because of the difficulties in estimating engineering costs for the diffuser manifolds. The water management, construction design, and project cost advantages and disadvantages will therefore need to be weighed up by Nelson City Council.

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1. INTRODUCTION

The Maitai River flows through Nelson city and is a significant recreational asset for the community. The river has important aesthetic values, frequented swimming holes and a trout fishery that (in the past) was ideally suited to junior anglers (Crowe *et al.* 2004). In addition to these values, the upper Maitai River is a vital part of Nelson's municipal water supply.

Operations of the Maitai water supply scheme in the Upper Maitai Catchment have the potential to affect the ecological health of the Maitai River further downstream through their effects on flow regime, water temperature, and water quality. This has been documented in a number of biomonitoring and water quality reports focusing on the Maitai River (Stark & Hayes 1996; Olsen 2010; Holmes 2010; Kelly 2014; Wood *et al.* 2015).

1.1. The Maitai Reservoir and water supply scheme

A 32 ha reservoir was built by Nelson City Council (NCC) on the North Branch of the Maitai just above the Forks (confluence with the Maitai South Branch) to augment the Nelson municipal water supply. It has been operational since 1987. The Reservoir is up to 29 m deep (at the dam wall), with a mean depth of 7.2 m. Water from the reservoir can be drawn from four levels via a valve outlet tower located near the foot of the dam, with water takes at 6 m, 12 m, 24 m, and 27 m (scour valve) of water depth based on full reservoir capacity (*i.e.*, water level at 173.2 m MASL).

Since its construction, there has been a consistent pattern of mid- to late-summer deoxygenation in the reservoir bottom waters owing to seasonal thermal stratification that extends from October through April (Kelly 2014). Stratification results in the development of discrete water layers: the epilimnion (warm surface layer), the metalimnion (*i.e.*, thermocline), and the hypolimnion (cool bottom layer). Anoxic conditions in the hypolimnion can develop as dissolved oxygen is consumed by water and sedimentary metabolism¹ without significant aeration from the lake's surface. In the Maitai Reservoir, anoxia typically persists in the bottom waters between February through to April (Kelly 2014).

Anoxia is highly undesirable because it results in poor habitat conditions for aquatic life in the reservoir, and promotes the release of harmful contaminants from sediments through biogeochemical cycling processes. Released contaminants include dissolved metals (principally manganese and iron), sulphides, and the solubilisation of metal-oxide bound nutrients (McQueen & Lean 1986; Kelly 2014). These contaminants can be flushed from the reservoir to the downstream river environment (Figure 1).

¹ mainly through decomposition of organic matter

The extent to which these contaminant release processes occur is dependent on the oxidation-reduction potential (REDOX) of lake bed sediments (Kinsman-Costello *et al.* 2015). From a reservoir management perspective, general rules such as keeping dissolved oxygen (DO) at > 50% saturation or > 5mg/L are effective because they are related to the REDOX of the lake bed, are tied with DO guidelines for aquatic life (e.g. ANZECC 2000), and are more easily (and commonly) monitored in field programs (Gibbs & Hickey 2012).



Figure 1. Picture of oxidised iron deposits on river substrate downstream of the backfeed weir in the Maitai River South Branch in April 2014 (Photo by P. Fisher, Nelson City Council).

Due to the poorer water quality within the reservoir, in comparison to the Maitai River under normal flow conditions, drinking supply water is abstracted directly from the South Branch of the Maitai River at the intake weir, rather than the reservoir. Abstracted Maitai River water is replaced by water from the Maitai Reservoir (termed the 'Backfeed') which is discharged at the foot of the intake weir (Figure 2). Reservoir water discharged to the South Branch from the backfeed is required to meet temperature conditions in the Maitai River. In late summer/autumn when river temperatures begin to decline, backfed water is usually extracted from the lower intakes (Intake 3 or Scour) of the reservoir in order to meet temperature consent requirements. However, the discharge of deoxygenated hypolimnetic water and associated toxicants (manganese, iron and hydrogen sulphide) is undesirable, and

may be contributing to the decline in stream-health observed at the monitoring site below the backfeed (Holmes 2010). It is therefore important to investigate potential options around reducing or rectifying issues associated with poor water quality being released from the reservoir. A parallel investigation is also being pursued, which examines the possibility of sourcing backfeed waters from oxic surface-layers in the reservoir (Hay & Allen 2015).

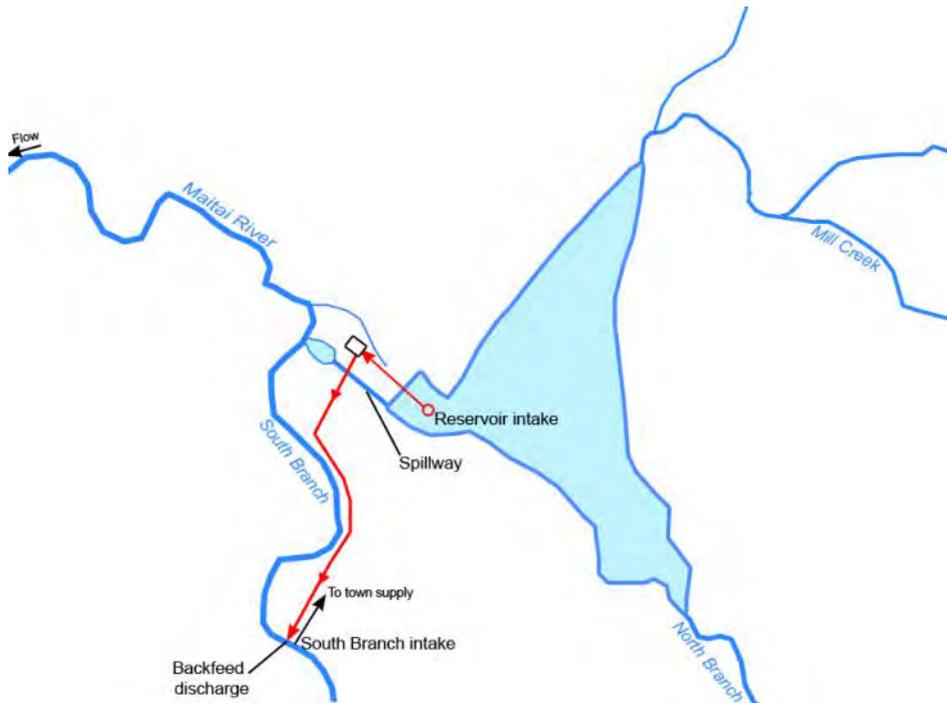


Figure 2. Diagram of the Maitai Water Supply Scheme with the water supply intake (labelled 'South Branch intake') and backfeed shown.

1.2. Project Maitai

Project Maitai/Mahitahi is Nelson City Council's (NCC) programme to improve the health of the Maitai River. It is focused on the Maitai River and some of its major tributaries including Brook and York streams, Groom and Sharlands creeks. The project is delivered in partnership with community group Friends of the Maitai, with input from key stakeholders and interested parties.

The programme of work for the 2014 / 15 year consists of 10 projects, including a number of initiatives focused on management of the Maitai Dam. These projects include investigations into:

- changes to dam operations, so that very low oxygen water is not fed back into the river from the reservoir with monitoring planned to see if this makes the expected difference to water quality in the river
- the costs and benefits of sourcing more drinking water from the reservoir rather than the South Branch
- a long-term solution to improve water quality in the reservoir and outflow water such as aeration of the reservoir or oxygenation of water, before it is backed to the river.

1.3. Purpose of this report

The consents held by NCC for the operation of the Maitai Reservoir expire in 2017. In anticipation of the re-consenting process, NCC has commissioned an assessment of reservoir aeration and mixing options for improving the water quality in the Maitai Reservoir with respect to hypolimnetic deoxygenation. This was one of the key recommendations previously identified to potentially manage water quality in the reservoir (Holmes & Kelly 2012). Leading up to this assessment, NCC have commissioned two other investigations to provide aquatic habitat, water quality, and physico-chemical environmental data. This data will be required to underpin a detailed assessment of reservoir aeration or mixing (Kelly & Shearer 2013; Kelly 2014).

This report provides detailed assessments of methods that could be employed to destratify (mix) or aerate bottom waters in the Reservoir. Following an initial review of the literature, a meeting between NCC and Cawthron identified three preferred options that were thought most applicable for managing hypolimnetic deoxygenation in the Reservoir. This included:

1. destratification of the reservoir through aeration mixing
2. hypolimnetic aeration through compressed air injection
3. hypolimnetic water transfer (pumping) using aerated surface waters.

Assessment of these three options will include detailed designs and required outputs of equipment (e.g., compressed air, water flow) to mix or aerate the reservoir at a rate sufficient to offset normal hypolimnetic deoxygenation. This includes an evaluation of the advantages / disadvantages of each method, and approximate capital and operational costs for each option.

1.4. Reservoir mixing and aeration approaches

Management measures to reverse and slow the effects of hypolimnetic deoxygenation have been tested extensively around the world (Ashley 1985; Cooke & Carlson 1989;

Schladow 1992; Wüest *et al.* 1992; Kortmann *et al.* 1994). These measures are essentially based on one of two mechanisms:

1. Reservoir destratification—the creation of upwelling water currents that act to break down physical stratification of the water column allowing surface-aerated water to circulate to bottom waters.
2. Hypolimnetic aeration—Introduction of oxygen (as air, water or liquid oxygen) below the thermocline at a rate sufficient to offset the rate of oxygen consumption.

There have been many engineering solutions by which these measures have been implemented in reservoirs. A review of the three potential and more commonly employed engineering solutions to reservoir destratification and hypolimnetic aeration are summarised in the following sections.

1.4.1. Destratification aeration mixing

The goal of a destratification device is either to prevent a water body from stratifying, or mixing an already stratified water body. It achieves this by introducing sufficient energy to disrupt the water column density gradient created by thermal stratification. If properly designed, an artificial circulation system will create isothermal conditions in a lake or reservoir. This can greatly improve water quality by oxygenating the water and preventing conditions that can lead to the formation of toxicants. This generally starts to occur when DO conditions decline below 5 mg/l (Cooke & Carlson 1989; Gibbs & Hickey 2012).

Destratification devices are most often designed around creating circular water currents through pumping compressed air to the bottom of the water column through diffuser ports (Fast 1968; Cooke and Carlson 1989). Compressed air exits the diffuser as fine-bubbles (3–5 mm) which entrain hypolimnetic water upwards as the bubbles expand and rise to the surface (Zic & Stefan 1990; Figure 3). Cooler denser water then sinks horizontally along density strata. Bottom water currents are entrained horizontally towards the diffusers to replace water that is entrained in the bubble plume.

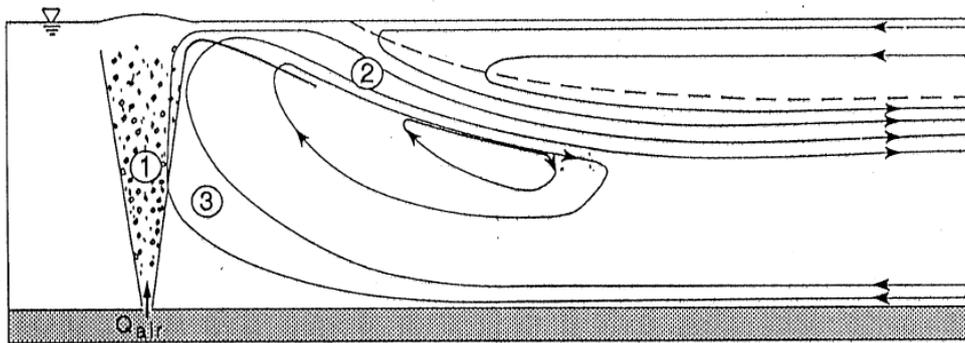


Figure 3. Theoretical water circulation pattern caused by vertical entrainment of the water column with a bubble plume mixer (modified from Zic & Stefan 1990). Circulation currents shown are (1) upwelling bubble plume current, (2) denser water downwelling to a lower depth strata, (3) horizontal hypolimnetic current entrained to the point of the bubble plume.

The effectiveness of air bubbles in entraining water currents is based on bubble size as well as the depth of the water column before the thermocline is reached in the mid-portion of the water column. The energy generated by the induced currents must be sufficient to break down the potential energy stored in the density gradient of the thermocline (Bernard *et al.* 2000). This density gradient can be measured from temperature profile data for the waterbody, with the destratification devices generally designed to mix the water column at its maximum thermal stratification gradient. In an operational environment, the compressors are left to operate for a period long enough to re-aerate the water column, typically a period of 1–2 weeks. After the destratification is completed, they may be shut off to reduce running costs.

Advantages to using destratification mixing devices for addressing hypolimnetic deoxygenation are:

1. energy efficiency - relying on surface aeration to reoxygenate the water column
2. capability of rapidly reoxygenating the water column should it become deoxygenated
3. mixing devices do not need to be left running continuously, and can be turned on when required to mix and re-oxygenate the water column.

Possible disadvantages of destratification include:

1. an overall warming of the hypolimnetic water which may slightly increase the DO consumption rate, and provide less cool water to discharge from the bottom outlet
2. a poorly designed destratification system can potentially increase nutrients and turbidity in the water body if it disturbs sediment layers or entrains nutrient rich water in the photic zone (Cooke & Carlson, 1989). Anchoring of the diffusers off the bottom sediment reduces the likelihood for this occurrence
3. upfront capital costs may be high, as large compressors are required.

In the context of the Maitai Reservoir, the main issues around hypolimnetic oxygen depletion have now been relatively well documented (Holmes & Kelly 2012; Kelly 2014). These include solubilisation of metals (manganese and iron) and hydrogen sulphide gas releases in reservoir bottom waters, which are subsequently discharged to the Maitai River during certain periods when cooler water discharges are required to meet temperature consent requirements (Kelly & Shearer 2013; Kelly 2014). There have been no observations of increases in hypolimnetic dissolved phosphorus (or nitrogen) over anoxia cycles. This is possibly related to redox pathways being dominated by calcium and sulphur metal oxide reduction over anoxic periods linked to upstream catchment limestone geology (Kelly 2014).

An effectively designed destratification system would correct problems associated with toxicant formation and subsequent downstream effects associated with this water into the Matai River. This would also improve the reservoir as a habitat for some species, which could utilise deeper water habitats during warm summer periods. A management trigger for initiating destratification mixing could be considered, such as DO approaching or breaching a 5 mg/l limit. This is a concentration value which marks the point at which manganese solubilisation in bottom waters occurs (Gibbs & Hickey 2012).

1.4.2. Hypolimnetic aeration

Hypolimnetic aeration involves oxygenation of the hypolimnion without disturbing the thermal-density gradient associated with stratification (Kortmann *et al.* 1994). The goal of the aeration is to add oxygen to the hypolimnion at a sufficient rate to offset oxygen consumption from biological and chemical oxygen demand. Hypolimnetic aeration has several advantages over artificial circulation, including:

1. an oxygen-enriched, cold-water habitat is maintained for fish species (e.g., trout, longfin eels)
2. normal summer temperature stratification allows flexibility in reservoir offtakes (through the backfeed) for meeting discharge temperature requirements
3. lower risk of transporting nutrients from the hypolimnion to the epilimnion where they can contribute to phytoplankton growth
4. aeration requires less energy and lower airflow rates to achieve hypolimnetic destratification, consequently smaller compressors may be used reducing initial capital outlay.

However, the approach also has some disadvantages, including:

1. it cannot be used to react quickly to low oxygen events
2. it must be operated continuously, potentially increasing operating costs.

McQueen and Lean (1986) reviewed the outcomes of several hypolimnetic aeration projects and summarised the results of the studies as follows: (1) well-designed aeration systems have maintained stratification and have not increased hypolimnetic water temperature significantly; (2) hypolimnetic oxygen levels increased; (3) iron, manganese, hydrogen sulphide decreased; (4) zooplankton populations were unaffected; (5) chlorophyll levels were usually not altered; and (6) depth distributions of cold-water fish populations increased. The effects of hypolimnetic aeration on phosphorus and nitrogen levels have been more variable. McQueen and Lean (1986) attribute this to pH levels and iron availability for phosphorus sedimentation.

In the context of the Maitai Reservoir, a well-designed hypolimnetic aeration system would rectify all of the issues in the reservoir associated with deoxygenation. A major advantage of hypolimnetic aeration (over hypolimnetic destratification) is the maintenance of seasonal thermal stratification patterns. This would preserve the existing ability to manage backfeed temperatures by changing (or mixing) the depth of the valve takes. This could allow release of cool hypolimnetic water to the Maitai River during late-summer and autumn periods when the river temperatures tend to be cooler than reservoir surface layers (Hay & Allen 2015). Consequently, it appears this management option is well aligned with objectives to improve the habitat quality of the lower Maitai River.

1.4.3. Hypolimnetic water transfer

Water oxidation ponds in some instances utilise water pumping systems rather than compressed air to exchange oxygenated surface layers with deoxygenated bottom waters. Typically this is accomplished through pumping of hypolimnetic waters to the surface of the waterbody. However, power usage typically limits the efficiency of such systems to waterbodies which are reasonably shallow (< 4 m deep). This is because of the energy usage associated with pumping large volumes from deeper depths (Cooke *et al.* 2013). Pumping of deoxygenated hypolimnetic water from the Maitai Reservoir hypolimnion would necessitate pumping from depths exceeding 20 m, and would be highly inefficient by comparison to aeration entrainment of water currents.

An alternative to pumping was considered by NCC which involves transferring (piping) oxygenated inflow water downwards through the reservoir water column into the hypolimnion. Inflows from the North Branch tributary are typically slightly cooler than reservoir surface waters, ranging between 11-14 °C under normal flow conditions. Therefore it is expected that surface water inflows are likely to sink below the surface level of the reservoir. However, they are warmer than hypolimnetic temperatures (9-11 °C) and therefore are expected to remain within the upper water column and unlikely to transfer significant amounts of dissolved oxygen to the reservoir hypolimnion. During larger flood events (e.g., > 35 m³/s for North Branch flows), entrainment of oxygenated surface water in to the reservoir hypolimnion has been shown to occur over short durations, as evidenced by changes in temperature and

dissolved oxygen levels in the upper hypolimnion measured around the valve tower (Kelly 2014).

Transfer of oxygenated surface water to the Maitai Reservoir hypolimnion would be accomplished via a water intake structure on the North Branch tributary, which because of its steepness, could potentially create hydraulic head sufficient to pump water to the depth required (estimated 15–20 m). A review of the international literature revealed only one example of where this has been attempted, in Lake Ballinger, Washington State, USA. In this instance, the combination of drawing water from the hypolimnion (*i.e.* outflow) and diverting tributary inflows into the hypolimnion decreased the rate of hypolimnetic deoxygenation and reduced the period when the lake was anoxic to approximately 2 weeks (KCM 1981). However, the inflow transfer was only to a depth of 4 m, and thus would have presented less of a challenge in designing a diversion structure.

Given the lack of information available on this approach, the engineering of the river water intake and transfer infrastructure for the Maitai Reservoir was considered beyond the scope of this investigation. However, at this initial feasibility stage several factors around this option were scoped as a possible management option. This included:

- rates of water transfer required to offset hypolimnetic deoxygenation rate
- hydraulic (and oxygen) retention of transferred river water in the hypolimnion given it is likely to be a rising plume of warmer, less dense river water
- the potential implications of the water diversion on environmental flows in the North Branch tributary.

1.5. Assessing feasibility of the options

The three options are evaluated in terms of three key aspects:

1. technical design and the likely ability to address hypolimnetic deoxygenation in the reservoir
2. capital and construction costs for the device design
3. ongoing operational and maintenance costs of the device.

These are summarised separately for each of the three potential options considered with advantages and disadvantages discussed in the recommendations section of the report (Section 4).

2. METHODS

2.1. Physico-chemical properties and stratification

Water column profiles of physico-chemical variables were undertaken over two years to characterise spatial and seasonal variability in stratification cycles, and estimate rates of hypolimnetic deoxygenation and thermal stratification strength (September 2013 to May 2015). In the first year, two sites were monitored that were representative of the open-water environment in the Reservoir (Kelly & Shearer 2013). However, following evaluation monitoring results in the first year, which found no difference between the monitoring sites (Kelly 2014), this was reduced to just a single site near the valve tower (W1) in 2014-15.

In situ lake measurements included: specific conductivity, Secchi depth, temperature, pH, DO, and light profiles. Specific conductivity, temperature, pH, and DO, were also analysed at approximately 0.2 m intervals between the Reservoir surface and 25 m using a YSI EXO multiprobe datasonde (YSI Inc. Yellow Springs, USA). Water clarity was quantified both using a Secchi disk, and by conducting underwater light profiles on a single date (13 February 2014) using a LICOR underwater LI-192SA photosynthetically active radiation (PAR) sensor (2π). This enabled PAR measurements from at least five depths.

To provide a more detailed temporal analysis of thermal stratification and DO conditions in proximity to the valve outlet-tower (near site W1), a thermistor chain was deployed that collected half-hourly temperature and DO data at multiple depths. The equipment was deployed between 22 September 2013 and 27 July 2014 and then again 7 November 2014 to 8 May 2015.

Specifically the second deployment included the following instrumentation:

- A thermistor chain, with temperature sensors (Hobo Temperature Pro v2, Onset Technologies, Cape Cod, Massachusetts, USA) that collected half-hourly temperature data at depths of 3 m, 8 m, 10 m, 14 m, 16 m and 18 m.
- Optical dissolved oxygen sensors (DO-Opto, Zebratech, Nelson, New Zealand) that collected half-hourly dissolved oxygen and temperature data at 6 m, 12 m, and 25 m, which correspond to the valve-tower outlet depths. Note that in 2014 / 15 the 6 m sensor was not deployed.

Optical sensors were cleared of biofouling during the monthly monitoring. Sensors were downloaded and calibration checks performed approximately every two months. There were no obvious signs of sensor drift during any of the 2-month logging periods, and therefore re-calibration was not required over the logging period.

2.2. Destratification aeration system modelling

System requirements for destratification aeration were based on three separate models, which take into account the amount of energy stored in the density stratification of the reservoir, and the energy provided by a bubble plume entrained current. A structured review of potential engineering solutions was undertaken by an external consulting firm (Hunter H₂O) on a range of methods spanning simple models to increasingly complex models.

2.2.1. Calculation methods (based on information supplied by Peter Greenhalgh, Hunter H₂O)

The simplest model used was that of Lorenzen and Fast (1977) who investigated empirical performance of standardized airflow rates in a number of different reservoirs. On the basis of their model, they concluded that an air flow rate of 9.2 m³/min/km² would be sufficient to provide destratification to storages under most conditions. The basis for this simple correlation of Lorenzen and Fast is shown in Figure 4. The correlation of Lorenzen and Fast (as presented in Bowersox 2002) is based on an approximate curve fit to existing data, and as such doesn't take into account the various aspects of lake morphology.

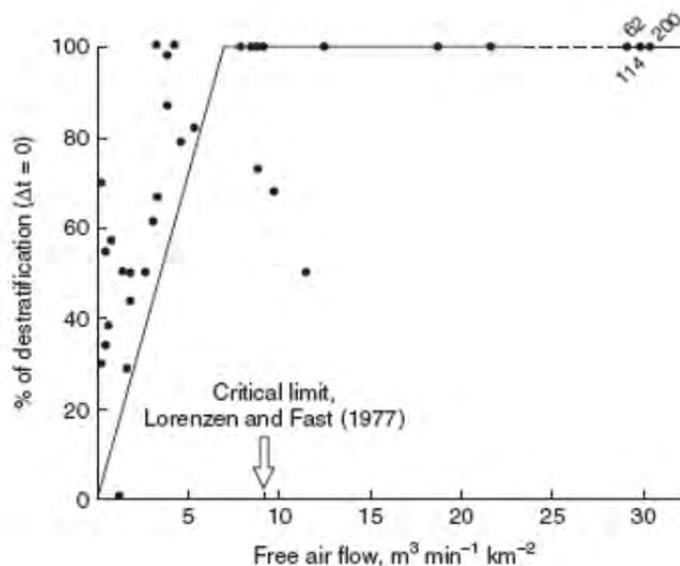


Figure 4. Lorenzen & Fast (1977) correlation between free air flow through a bubble plume and the proportion of destratification in reservoirs.

A more recent design methodology was produced by Davis (1980) and uses the lake morphology in its calculation of the required airflow rate for reservoir destratification. The steps involved in calculating the required airflow rate according to the Davis method include the calculation of the stability criteria and also incorporate morphological information; these calculations are detailed in the following text.

The stability of the reservoir is the difference between the potential energy of the stratified lake compared with the potential energy of a totally mixed lake. The calculation of stability from Davis (1980) is described below following the nomenclature presented in Bowersox (2002):

$$S = g \sum_{i=1}^n \rho_{im} V_i h_i - g \sum_{i=1}^n \rho_{is} V_i h_i$$

Where: S = Stability, joules; g = acceleration due to gravity, m/s²; ρ_i = density of layer i, kg/m³; V_i = volume of layer i, m³; h_i = height of centroid of layer i, m; m = mixed, s = stratified.

The energy required for destratification is calculated by:

$$E=S+R-W$$

Where S = stability, R = heat input, and W = wind energy, all in joules.

In order to provide the required airflow rate, Q (in l/s), for destratification, Bowersox (2002) states that:

$$Q = \frac{0.196E}{T \ln\left(1 + \frac{D}{10.4}\right)}$$

Where E = energy input required, T = time to achieve destratification, D = depth of diffuser, 10.4 = the depth of water equivalent to 1 atmosphere of pressure.

The volume of air entrained by air bubbles released by the diffuser pipe can be calculated according to the following equation (as presented in Bowersox 2002):

$$V_e = 0.486LT \left(\frac{gQ}{L}\right)^{1/3} \left(1 + \frac{D}{10.4}\right)^{-1/3} \ln\left(1 + \frac{D}{10.4}\right)$$

As the volume of the lake and the required airflow rate for destratification are known, the length of the diffuser airline can now be calculated.

The latest method for the calculation of the required airflow rate for destratification of lakes and reservoirs is that of Schladow (1992). The method has been described to provide better efficiencies as it *“is based on the fluid dynamics of bubble plumes ascending through stratified water”* (Lemckert *et al.* 1992).

The method of Schladow (1992) is similar to the method of Davis (1980) as the first step is calculation of the potential energy required to destratify the reservoir ΔPE (J). Once the potential energy has been calculated then the potential energy per unit area for the reservoir PE_A can be calculated (J/m^2). Using the above information the linear buoyancy frequency N_E for the reservoir can now be calculated, as described by Lemckert (1992).

$$N_E = \left(\frac{1/2 \rho_B g h^2 - PE_A}{1/3 \rho_B h^3} \right)^{1/2}$$

Where ρ_B is the water density at the diffuser depth and h is the height of water above the diffuser.

Once the linear buoyancy frequency has been calculated, Q_M , Q_P and Q_R , need to be calculated, where (Lemckert 1992):

$$Q_M = \frac{4\pi\alpha^2 h v_s^3}{g}, \quad Q_P = \frac{N^3 h^4}{g} \quad \text{and} \quad Q_R = \frac{Q_P}{Q_M}$$

Where α = entrainment coefficient ~ 0.083 , N = buoyancy frequency, rad/s, v_s = slip velocity of the bubbles relative to the rising water plume ~ 0.3 , m/s.

The value of Q_R can then be substituted into the following equation to determine Q_B , the air flow rate from single diffuser at depth

$$\frac{N^3 h^4}{Q_B^* g} = 10^{[0.16 \log(Q_R) + (2.1 H_R - 0.55 H_R^2)]}$$

Where $H_R = h/H_T$, where H_T is the total pressure at diffuser depth in m of water.

The value of Q_B can then be used to calculate M_H , which represents the source strength compared to a water depth pressure, using the following equation (Lemckert 1992):

$$M_H = \frac{g Q_B}{4\pi\alpha^2 h v_s^3}$$

Once M_H is known the required airflow rate at the diffuser depth pressure, Q_f can be determined using the following equation (Lemckert 1992):

$$Q_f = 0.56 \left(\frac{(Q_B^* g)^3}{N_E^5} \right)^{1/4} M_H^{0.11}$$

Once Q_f is known the number of diffuser ports required m^* can then be calculated using the following equation (Lemckert, 1992):

$$T_V = \frac{\Delta PE}{m^* Q_f}$$

Where T_V is the time taken to destratify the reservoir in seconds. The required airflow rate can then be calculated by multiplying the required airflow rate per diffuser port by the number of diffuser ports required.

2.2.2. Summary

Calculations undertaken using these methods have been provided by an external consultant (Peter Greenhalgh, engineer, Hunter H₂O) for feasibility assessment purposes and were based on collected data provided by the author of this report. Outputs of all of the three methods are provided as a basis for assessing the feasibility of different aeration system requirements. Although all three methods are presented, it is considered that the method of Schladow (1992) provides the most reliable estimate and is used the basis for system requirements in subsequent costings.

2.3. Hypolimnetic aeration

System requirements for a hypolimnetic aeration system were based on the total hypolimnetic oxygen consumption that occurred between the months of October through April (*i.e.* six months) over two consecutive monitoring years, from 2013 to 2015. This was based on thermistor chain monitoring data showing the reservoir stratified in October and with autumn turnover occurring in either late April or early May.

Rates of hypolimnetic oxygen consumption were calculated from continuous dissolved oxygen concentration data collected at 24 m depth. Volumetric hypolimnetic oxygen decline rates (VHOD in g O₂/m³/d) were multiplied by the volume of the hypolimnion to obtain the total oxygen consumption rate in the hypolimnion. Monthly hypolimnetic volume was calculated using monthly temperature profile data collected at approximately 0.2 m depth intervals between the reservoir surface and 25 m using an YSI EXO multiprobe datasonde (YSI Inc. Yellow Springs, USA). The upper boundary of the hypolimnion used for calculating hypolimnetic volume was considered to be the mid-depth of the thermocline. The hypolimnetic volume was calculated using a previously derived digitised reservoir bathymetry map (Kelly 2014).

Monthly hypolimnetic aeration rates required to offset hypolimnetic deoxygenation were calculated based on separate two criteria:

- 1) Aeration rate sufficient to maintain hypolimnetic dissolved oxygen concentration greater than 5 mg/L
- 2) Aeration rates sufficient to completely offset hypolimnetic deoxygenation.

Aeration airflow rates accounted for a proportion atmospheric oxygen content of 23.2% (by mass). Therefore, all calculations of airflow rates are for atmospheric air, which could be reduced if a purified oxygen source was considered.

2.4. Hypolimnetic water transfer

As for hypolimnetic aeration, the system requirements for a hypolimnetic inflow water transfer system were based on offsetting the total hypolimnetic oxygen consumption that occurred between the months of October through April (*i.e.* six months). This was based on thermistor chain monitoring data between 2013 and 2015.

Rates of hypolimnetic oxygen consumption were calculated from continuous dissolved oxygen concentration data collected at 24 m depth. Volumetric hypolimnetic oxygen decline rates (VHOD in $\text{g O}_2/\text{m}^3/\text{d}$) were multiplied by the volume of the hypolimnion to obtain the total oxygen consumption rate in the hypolimnion. Monthly hypolimnetic volume was calculated using monthly temperature profile data collected at approximately 0.2 m depth intervals between the reservoir surface and 25 m using a YSI EXO multiprobe datasonde (YSI Inc. Yellow Springs, USA). The upper boundary of the hypolimnion used for calculating hypolimnetic volume was considered to be the mid-depth of the thermocline, and converted to hypolimnetic volume using a previously derived digitised reservoir bathymetry map (Kelly 2014).

Monthly water inflow rates required to offset hypolimnetic deoxygenation were calculated based on two criteria:

- 1) Dissolved oxygen concentration of inflowing waters measured in tributary inflows
- 2) Retention rates of dissolved oxygen contained in the inflowing plume within the reservoir hypolimnion (via a diffuser manifold).

Dissolved oxygen concentration data for the North Branch tributary inflow were obtained from a combination of instantaneous and continuous monitoring data collected between 2013 and 2015. For some time periods there were no DO data available for the North Branch tributary. For these months, information from the Maitai River South Branch, upstream of the backfeed, was used as an alternative. Patterns in dissolved oxygen concentration and temperature were compared between North and South branches to ensure this would not distort calculations.

Retention of transferred water within the hypolimnion is expected to vary depending on the volume of water transferred and differences in density between inflow water and reservoir hypolimnetic water. It is expected over most summer months that the temperature of water transferred from the North Branch tributary would exceed that of the hypolimnion. As such we would expect that the warmer, less dense, water plume would rise through the reservoir water column as it mixed with hypolimnetic water.

Mixing dynamics of water plumes can be modelled using effluent dispersion models such as Cormack Software, and this was intended to be conducted following an initial calculation of water transfer rates that would be required to offset deoxygenation. However, initial calculations revealed that very high flows (on average 129 l/s) would need to be diverted from the North Branch to offset hypolimnetic deoxygenation occurring in the reservoir, and these water transfer rates would at times exceed flows available in the North Branch tributary. Therefore it was considered that the approach for reversing hypolimnetic deoxygenation would not be viable for the Maitai Reservoir, and further dispersion modelling was not pursued. All calculations of water transfer rates required to offset hypolimnetic deoxygenation were therefore calculated based on 100% retention of water within the hypolimnion, recognising this is only to provide an indication of the requirements of the hypolimnetic inflow transfer under optimum retention.

3. RESULTS

3.1. Destratification aeration

Over the two years of continuous temperature monitoring, the intensity of thermal stratification in the reservoir started increasing in September, progressively deepening the thermocline extent between October and April (Figure 5). The maximum difference in temperature between surface and bottom waters occurred during late February in both monitoring years. This period is when stratification was strongest, and therefore would require the greatest energy to break down the thermocline. There were some small differences in stratification patterns between years; however, the timing of thermocline development and breakdown were consistent between the years. The thermocline extent was deeper in 2014 by comparison to 2015.

The strength of the thermocline can be quantified by calculating the potential energy anomaly (PEA), which takes into account the rate of water density change over the depth of the water column (Figure 6). The PEA value is informative for determining the energy output requirements of a destratification mixing system, with a robust system designed to break down the water column at its peak PEA level. For both years of monitoring in the Maitai Reservoir, PEA increased relatively constantly onward from September to as high as 50 J/m^3 around the end of February. The effects of floods (in inflows) can be seen on several occasions where sharp declines in PEA occurred during January and March in both years. Overall, PEA was greater during 2014 to 2015 by comparison to the previous year, most likely a consequence of warm-dry summer conditions that occurred in the second year of monitoring. The overlap of the monitoring period with warm-dry summer conditions is useful, because it provides assurance that stronger stratification cycles are accounted for in the system design.

The timing and frequency for destratification mixing can vary depending on thresholds established by NCC. For example, these could be specified in terms of acceptable levels of deoxygenation in bottom waters of the reservoir. Should a dissolved oxygen cut-off of 5 mg/L be used, as recommended by Gibbs and Hickey (2012), this would necessitate that an initial destratification mixing event would need to occur in December based on rates of DO decline observed between 2013 to 2015 (Figure 6b). Following this initial destratification mixing period, an aeration device could either be left to operate (at a lower airflow) to maintain a homogeneous water column, or turned off after a period of mixing and the reservoir allowed to re-stratify and progress through another deoxygenation cycle. The DO cut-off is therefore important for determining the frequency of further mixing events over the seasonal stratification cycle, and would influence the operational costs for the destratification system. This is considered in greater detail in the section examining operating costs.

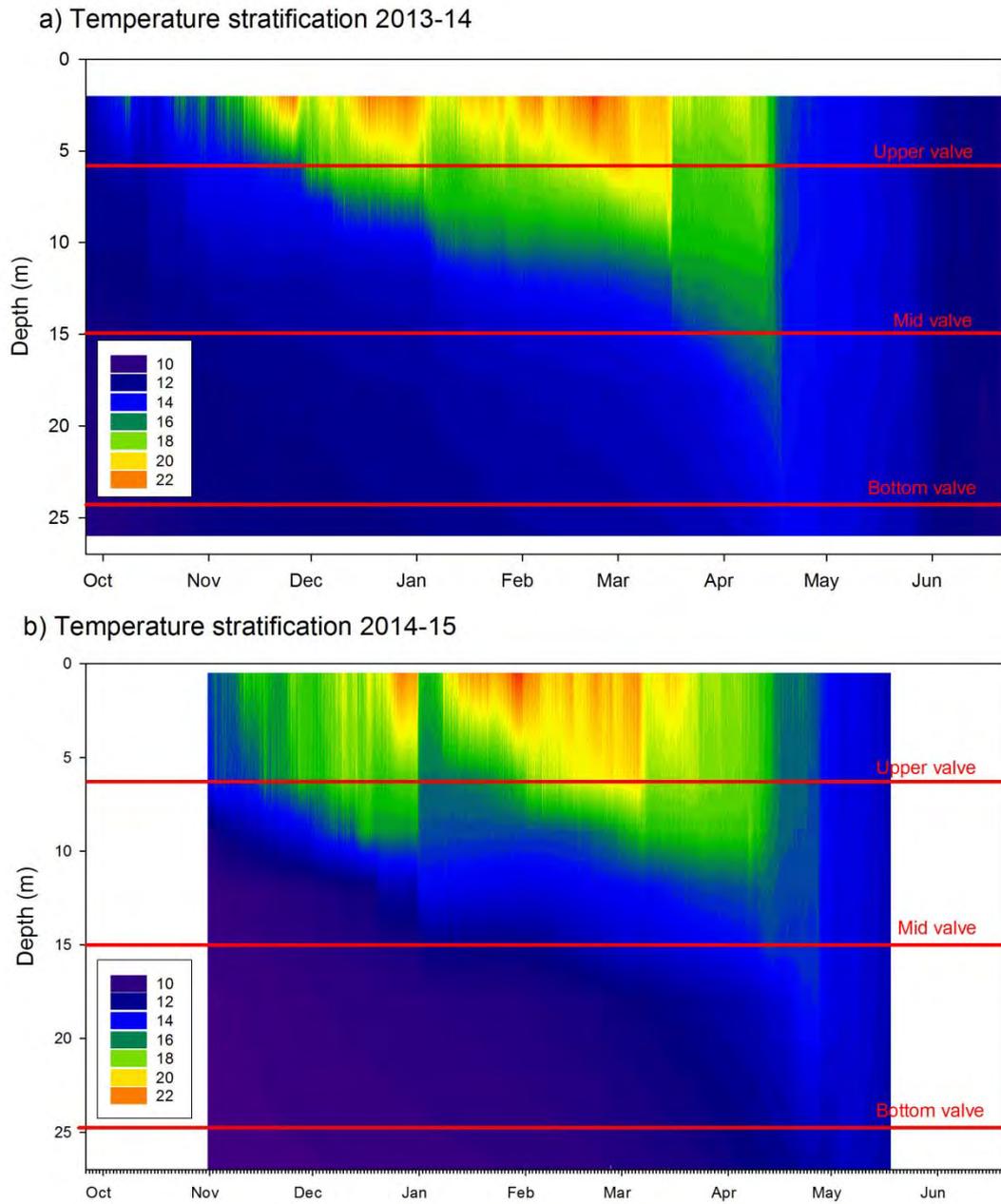


Figure 5. Temperature stratification patterns over two summers in the Maitai Reservoir, with the overlaid red lines showing the depths of the valve tower outlets.

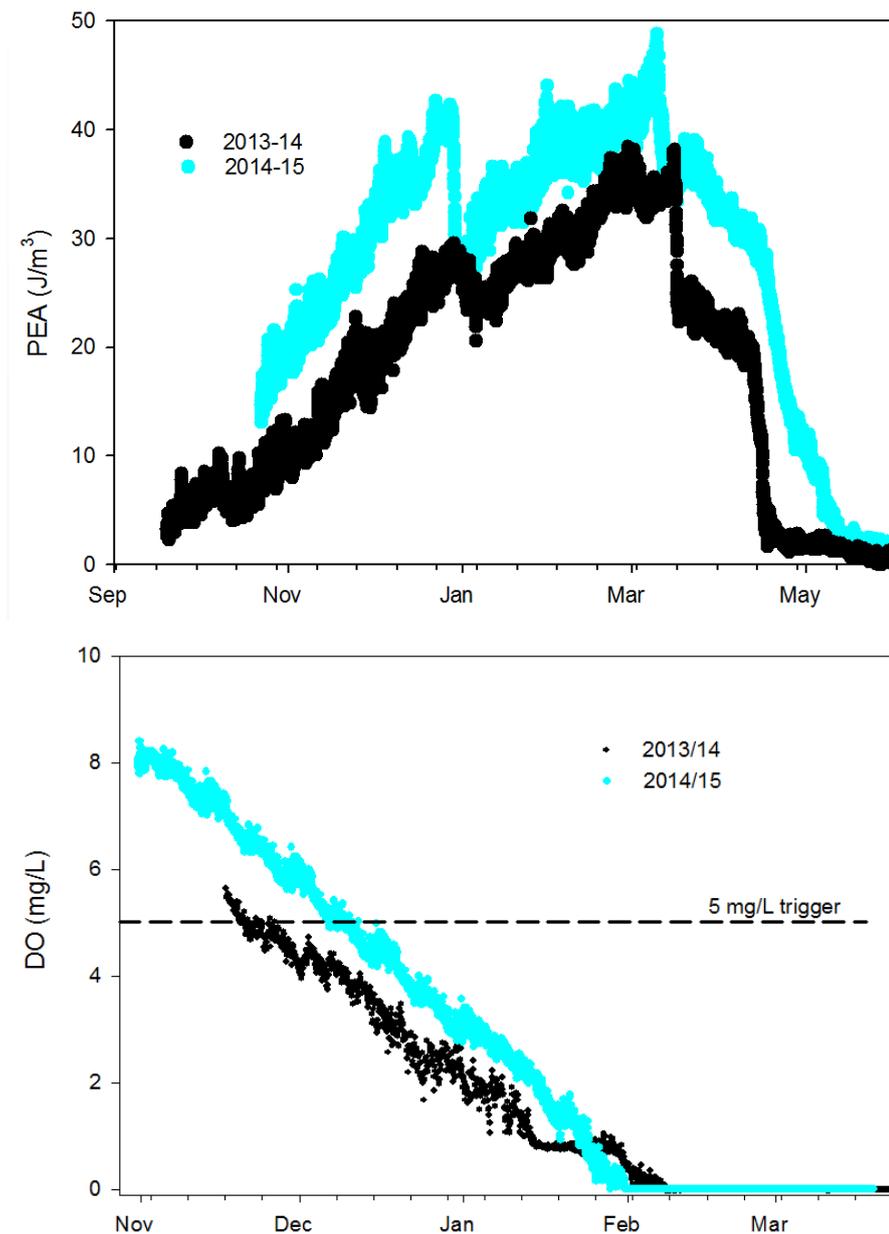


Figure 6. Seasonal trend in the (a) potential energy anomaly of the Maitai Reservoir water column (upper) and (b) dissolved oxygen (DO) at 24m depth (lower). Note the development of stratification and subsequent breakdown and associated reduction in DO over the summer period.

3.1.1. Considerations for the design of the destratification system

The Maitai Reservoir is a small reservoir in terms of surface area and volume. The dam is an elongated shape with a bend in the middle which may present some hindrance to mixing from an aeration system. The best location for an aeration line is in the deepest part of the reservoir through the centre, running east-west. This positioning should provide optimum destratification potential but some stratification

may occur in the upper extents of the reservoir. Key data for the design of the destratification system in the Maitai Reservoir included:

- maximum operating depth – 32 m
- maximum storage volume – 4.4 GL
- maximum surface area – 32.1 ha.

The period at which maximum thermal stratification occurred was used in sizing of the compressor and air distribution pipework. This occurred in late February where surface temperatures and bottom waters differed by approximately 12°C (Figure 7).

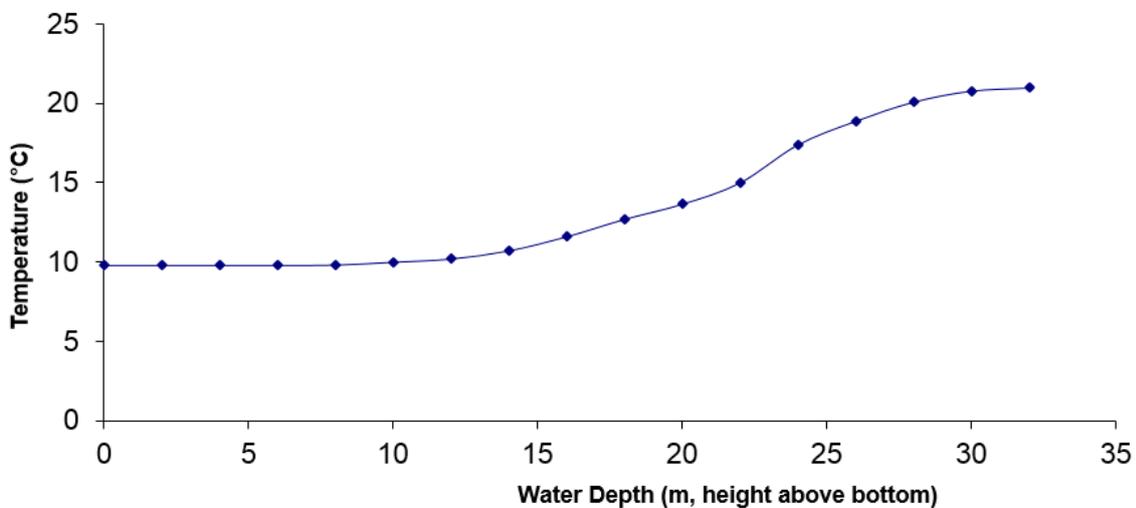


Figure 7. Temperature profile data used for designing output of a destratification mixing system taking into account the maximum summer difference between surface and bottom waters.

To ensure that the destratification system can effectively mix the reservoir, a system designed for destratification over 10 days was selected. Selecting a shorter (more compressor airflow) or longer (less compressor airflow) design for destratification time may be suitable, but would need to be considered in future investigations.

Modelling conducted for this study identified that a total of 8 bubble port diffusers at 20 metre centres would be required with a design air flow rate of 3.4 l/s per diffuser. The diffuser structures would be situated at approximately 0.5 m from the bottom sediments (anchored and floated above the bed of the reservoir). The total diffuser airline was estimated at 165 m in length with a recommended siting of the line along the central basin of the Reservoir (Figure 8). Modelling results were provided by an external consultant and are detailed for all three methods in Appendix A. As noted in the methods section although all three methods are presented, it is considered that the method of Schladow (1992) (labelled as ‘Schladow & Imberger’ in the appendix) provides the most reliable estimate. This result is used as the basis for system requirements in subsequent costings.

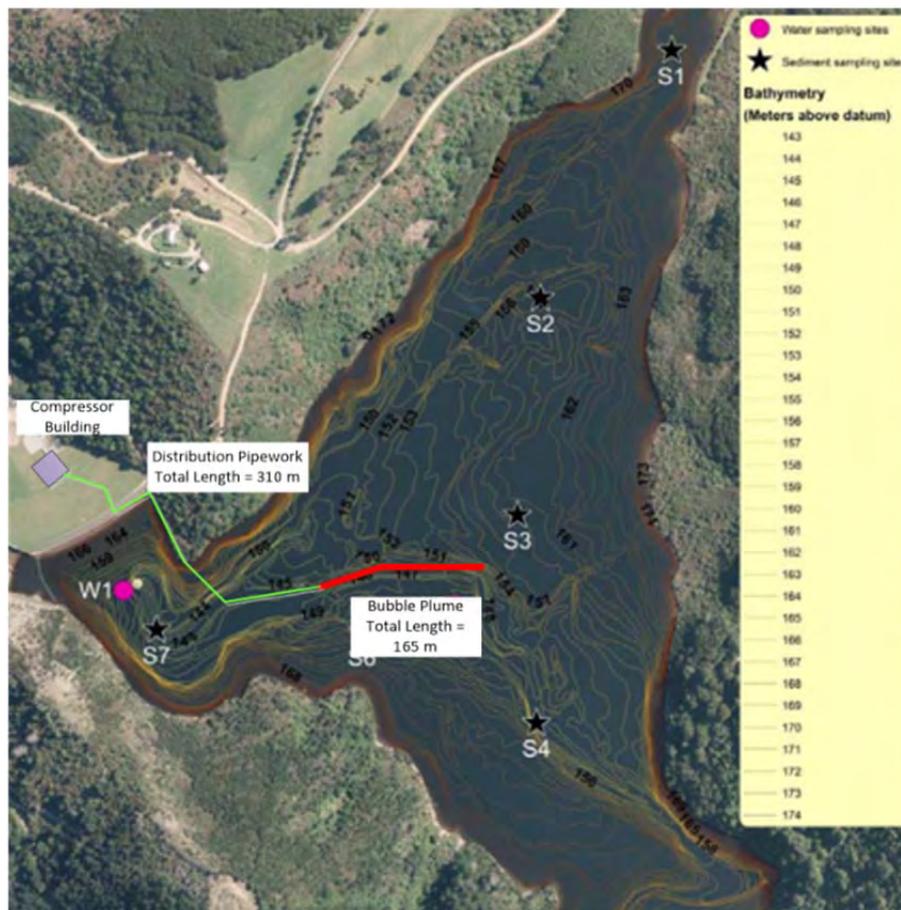


Figure 8. Destratification system layout on the Maitai Reservoir showing the location of the 165 m sparge line and connection with compressor building at the foot of the dam. Also shown are water (W1) and sediment (S1-S7) quality monitoring sites for the reservoir.

Based on the provided calculations, the destratification system would therefore include:

1. a pair of 15 kW duty/standby variable speed water injected screw compressors
2. a total free air flow rate of 30 l/s
3. a building to house the duty/standby compressors (possibly tied in with existing pump house)
4. electrical supply to the compressed air system
5. approximately 310 m of feed pipework from the compressor building to the air line
6. pipe lagging, fixings and condensate traps
7. a 165 m air line with 8 outlets at 20 m centres
8. airline anchor blocks and floats to keep the airline out of the sediment
9. the air line would be at an approximate depth of RL 31 m.

The use of variable speed compressors has been selected, as it will enable power savings during times when the minimal destratification energy input from the bubble

plume system is required. Consideration may also be given to the supply of one compressor only, however this would require further discussion with suppliers.

Consideration by NCC could also be given to the possibility for the intermittent operation of the destratification system when dissolved oxygen levels in the hypolimnion reach a threshold level. This would potentially reduce operational costs in terms of total power usage over the stratification season. Modelling of dissolved oxygen fluctuations under an intermittent operating regime was conducted based on the destratification system being activated at a hypolimnetic DO cut-off of 5 mg/l (Gibbs & Hickey 2012), and the operation of the destratification occurring over a 10 to 14 day period. Following each mixing period, the destratification system was turned off, and the reservoir allowed to re-stratify and progress through another deoxygenation cycle. Rates of bottom water oxygen depletion were based on continuous DO and thermistor chain data collected between 2013 and 2015. Modelling of deoxygenation rates were not able to not account for hypolimnetic water that could potentially be further warmed subsequent to destratification mixing. This could potentially affect the rate of hypolimnetic oxygen depletion to a small extent.

Based on modelling results, it was predicted the reservoir would need to be destratified three times over the course of the stratification season (*i.e.*, October-May; Figure 9). The requirement for three mixing events was consistent for both years of monitoring data considered. Based on this, it is predicted that the destratification system will need to be operated over a period of six weeks annually. The implications, in terms of effects on operational costs, are detailed in section 3.1.2.

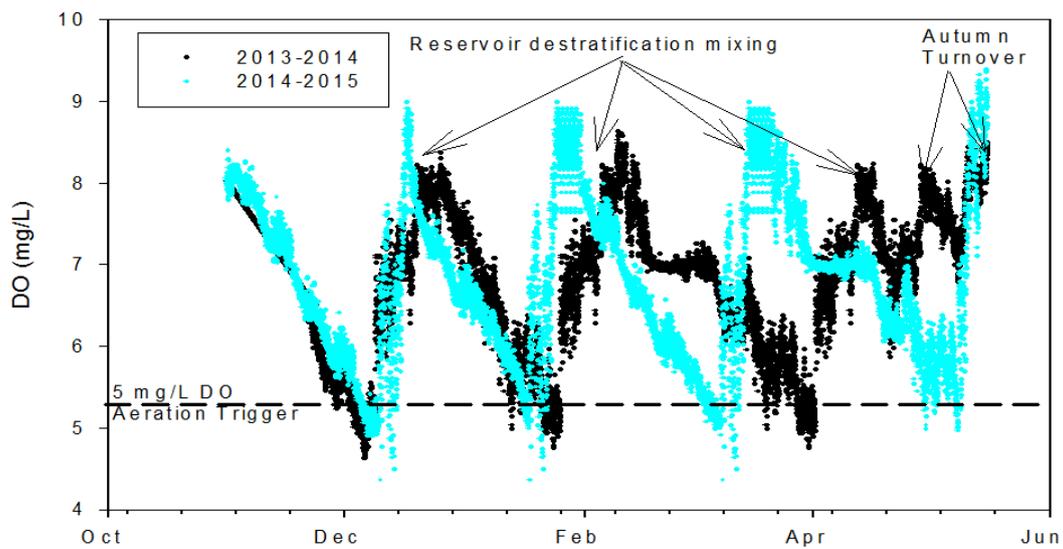


Figure 9. Dissolved oxygen model predictions for the Maitai Reservoir during the 2013 to 2014 and 2014 to 2015 summer seasons with destratification mixing. Modelling assumes destratification mixing can increase water column DO to 8 mg/L operated over a two week period. Oxygen decline rates were calculated from actual deoxygenation rates over the stratified period.

3.1.2. *Destratification System Cost Estimate (provided by HunterH2O)*

Summaries of the capital cost estimates for the provision of a bubble plume destratification system for the Maitai Reservoir are detailed in Appendix B. A detailed breakdown of the cost estimate is also attached in Appendix B. Where applicable, quotations were obtained directly from suppliers for any major equipment items and included delivery costs to the Nelson area. The remaining costs were generated using previous tendered costs, and an independent consultant's cost database for other costs.

Table 1. Capital cost estimate of a destratification system for the Maitai Reservoir. Note costs were provided with input from HunterH2O based in New South Wales

Parameter	Variable	Cost
Site preliminaries & general construction		\$ 18 K
Compressor building		\$ 67 K
Compressors		\$ 160 K
Feed pipework & associated equipment		\$ 56 K
Air distribution pipework & fittings		\$ 55 K
Electrical works		\$ 302 K
Sub Total		\$ 656 K
Contractor overheads & profit	18%	\$ 118 K
Project management	5%	\$ 33 K
Base Cost		\$ 807 K
Contingency	30%	\$ 242 K
Total Capital		\$ 1,049 K

During the preliminary stages of design it is only possible to estimate approximate quantities of major civil and mechanical items required, such as key process equipment (*i.e.* aeration), earthworks, concrete volumes and pump sizes/costs. A separate contingency of 30% is therefore added to account for minor scope changes and changes in equipment and/or construction costs (Table 1).

Specifically the total contract cost estimates for this project include the following estimated allowances:

1. contractor overheads and profit @ 18% of subtotal of civil, mechanical and electrical
2. project management @ 5% of subtotal of civil mechanical and electrical
3. contingency @ 30% of subtotal of civil mechanical and electrical.

Additional costs may be incurred due to the need for power supply upgrades and / or the presence of unfavourable geotechnical data. Furthermore, no allowance has been made for encountering significant submerged objects when installing the air line. To reduce the cost of the compressor installation, it may be possible to use temporary buildings such as the one pictured in Figure 10.



Figure 10. Examples of temporary container buildings used for housing destratification compressor systems.

3.1.3. Operational costs

The monthly temperature differential profile shows that destratification of the reservoir may be required for seven months of the year on average. Based on a six month per year usage of the destratification system, the estimated annual operating cost is in the order of:

- \$3,643 *per annum* for mechanical maintenance based on 1.0% of capital spend
- \$2,265 *per annum* for electrical maintenance based on 0.75% of capital spend
- \$13,608 *per annum* for electrical power based on \$0.18 per kWh.

If intermittent operation of the destratification system was effective this could reduce the overall power usage costs as follows:

- \$2,722 *per annum* for electrical power use if operated intermittently estimated on 6 weeks *per annum* based on \$0.18 per kWh.

The total operating (power) and maintenance cost is therefore estimated to be \$19,516 *per annum* (if operated continuously over six months) and \$8,630 *per annum* if operated intermittently. Additional allowance will also be required for maintenance of civil structures over the longer term.

3.2. Hypolimnetic aeration

Several designs of hypolimnetic aerators have been used in lakes and reservoirs (Fast & Lorenzen, 1976). Three of the most commonly employed designs include full (or partial) lift aerators, Speece cones, and bubble plume diffusers. A brief outline of each functionality is described in the following section, which is based on an extensive review by McGinnis (2000).

There is considerable complexity around the design and performance efficiency of hypolimnetic aeration systems. A number of parameters must be optimized to local reservoir conditions (e.g. depth of hypolimnion, temperature gradients, oxygen depletion rates), and the designs of the diffuser and manifolds are often system specific (Ashley & Hall 1990). Relatively small changes in design can result in significant variation in the system's performance (McQueen & Lean 1986; Wüest *et al.* 1992). In this respect, it was difficult within the scope of this feasibility study to make detailed predictions of system requirements, without further detailed engineering design works being undertaken.

3.2.1. Full- and partial-lift hypolimnetic aerators

Full- and partial-lift hypolimnetic aerators consist of diffusers that supply an air-bubble flow into a long riser tube and one or more 'downcomer' structures that return oxygenated water back to the water column below the thermocline depth (Figure 11). Full-lift aerators extend from the reservoir bed to the water surface where it is open to the atmosphere, whereas partial-lift aerators are sealed at the top (except for the exhaust pipe), and remain submerged. In both devices, air bubbled into the riser tube creates an upward water current of less dense bubble-water mixture. As the bubble-water mixture rises through the hypolimnion, oxygen is dissolved into the water from the bubbles. Gas bubbles exit the water (via a water/air separator exhaust manifold) and oxygenated water is returned to the hypolimnion via the downcomers. Water velocity through the riser and downcomers is a function of the volume of air injected and the diameter of the bubbles. The performance of such devices generally improves with reservoir depth because of the increased time period bubbles can exchange with the water column, and is poor in shallow reservoirs (< 10 m depth).

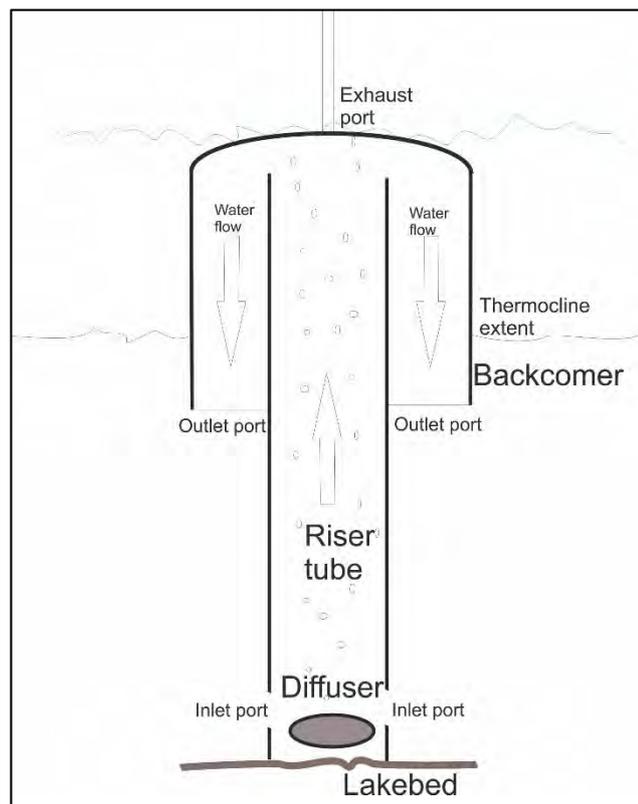


Figure 11. Schematic of the typical full-lift aerator showing main features of the riser tube, downcomers, and diffuser. Air is introduced as fine bubbles through the diffuser, creating water currents that travel through the inlet ports, up the riser tube and down the downcomers where they exit the aerator.

Diffuser dimensions and airflow rate are very important for controlling rise velocity and therefore the amount of time bubbles remain in contact with the water column. Probably the most important factor is the size of bubbles formed from the diffuser, with very fine bubbles (typically 2-3 mm diameter) providing optimum velocity rates and gas exchange to the water column.

3.2.2. Speece cone

The Speece Cone consists of a conical chamber with the large diameter of the cone resting near the bottom of the reservoir (Speece *et al.* 1973). Water is introduced to an opening at the top of the cone via a submersible pump. Air, or pure oxygen, bubbles are also introduced at the top of the cone with a bubble diffuser and migrate slowly down the cone as they dissolve into the pumped water stream. The discharge from the cone is located at the base where the highly oxygenated water is introduced to the hypolimnion via a diffuser. The water velocity is faster than the bubble rise velocity, which results in gas bubbles being slowly dragged downwards in the cone. This allows rapid dissolution of oxygen and high oxygen transfer efficiency, which is due to the increasing hydrostatic pressure from the bubbles travelling downward. Because gas transfer is determined principally by pumping rate, rather than upward

rise velocity, these devices are suitable for shallower reservoirs (*i.e.*, < 10 m) where transfer from a rising bubble plume would be less efficient.

Hydrodynamically, this is one of the simplest devices, because the water velocity is known based on the cone geometry and the pump capacity. As with the full-lift hypolimnetic aerators, bubble size is also an important factor in determining the gas transfer efficiency. Efficiencies of up to 92% gas transfer have been reported using this approach (McGinnis 2000).

3.2.3. Bubble plume diffusers

For bubble plume aerators, air or oxygen bubbles are introduced into the bottom of the reservoir via a large unconfined diffuser (*e.g.*, circular or long rectangular diffusers; Wüest *et al.* 1992). These devices are similar in principle to hypolimnetic destratification devices, however bubble diameter is much smaller and the gas transfer rate lower so as to not induce rapid upwelling gas-water plumes capable of modifying the overlying thermocline. Similar to the full-lift aerators, as the bubbles are introduced into the water in the hypolimnion, the bubble-water mixture becomes less dense than the surrounding water, inducing an upward velocity. As the plume water rises, the oxygen dissolves from the bubbles traveling with the water until the plume loses its vertical momentum. Oxygenated water falls back to the layer of neutral buoyancy (Wüest *et al.* 1992). Remaining oxygen in the bubbles continue to be transferred to the surrounding water until the bubbles are completely dissolved or they pass through the thermocline.

Hydrodynamic and oxygen transfer properties of bubble plume diffusers are complex because the plume is unconstrained and can interact with the water column to entrain water as it rises upwards through the thermocline. Given the uncertainties around oxygen exchange rates and hypolimnetic mixing around bubble plume diffusers, this would be seen as the least certain option. The number of diffusers and their placement would greatly depend on water column mixing, and therefore if this option was considered it would have to be using an adaptive approach to determine efficiency.

3.2.4. Predicting hypolimnetic aeration system requirements

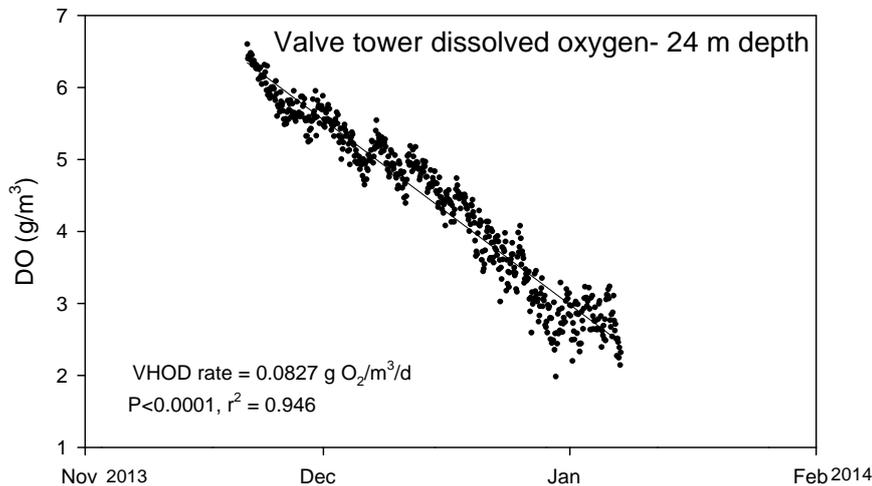
Reservoir hypolimnetic aeration requirements were predicted from volumetric hypolimnetic oxygen depletion (VHOD) rates in the reservoir hypolimnion at 24 m depth (Burns 1995). There was a strong fit of a linear model to the dissolved oxygen data obtained for both years of monitoring (r^2 of linear model > 0.946, Figure 12). This suggested a relatively stable rate of DO decline in bottom waters, with little exchange of reaerated surface water across the thermocline. Rates for the 2013-14 and 2014-15 stratification seasons were similar between years, being an average rate of 0.084 g/m³/d.

Monthly rates of hypolimnetic aeration required to offset deoxygenation were made considering two main factors.

- 1) monthly variation in volume of the hypolimnion
- 2) oxygen transfer efficiency of the aeration device.

Total volume of the hypolimnion diminished over the progression of stratification as the depth of the thermocline depth deepened until January, and then progressively increased through to April. This meant that hypolimnion volume was initially around 3.89 million cubic meters in early spring (October), but then declined by over 70% to 1.37 million cubic meters in January. This seasonality had a very pronounced effect on aeration airflow requirements to offset hypolimnetic deoxygenation. Airflow rates were as high as 17.1 l/s in spring and as low as 6 l/s in mid-summer.

a) Hypolimnetic dissolved oxygen 2013-14



b) Hypolimnetic dissolved oxygen 2014-15

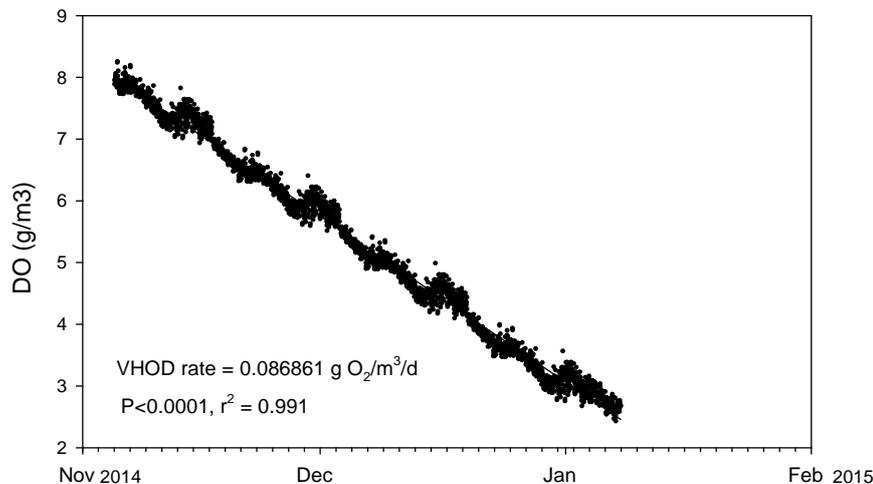


Figure 12. Volumetric hypolimnetic oxygen depletion rates (VHOD) measured at 24 m depth over two seasonal stratification cycles in the Maitai Reservoir.

As previously discussed, the efficiency of the aeration device in transferring oxygen to the water column is difficult to accurately predict. Efficiency depends on a number of factors such as the partial pressure coefficients of gases in the water column, bubble diameter, velocity of water within the aeration unit, and depth of the water column. Therefore, the efficiency of the hypolimnetic aeration unit was not able to be addressed in detail as part of this initial feasibility investigation. However, aeration rates were calculated based on oxygen transfer efficiency data reported from previous studies and reviews, and assumed such a device could be operated with an oxygen transfer efficiency ranging between 60-92% (McQueen & Lean 1989; Wüest *et al.* 1992; Burris & Little 1998; McGinnis 2000). There were unfortunately no case studies of hypolimnetic aeration devices being used in New Zealand lakes and reservoirs, and therefore the design and implementation of such a system would likely have to come from overseas experience.

Based on the range of oxygen transfer efficiencies and patterns in seasonal hypolimnetic volume, the average airflow rates through the hypolimnetic aeration system is estimated to be between 5–7 l/s (Table 2). Based on maintaining hypolimnetic DO concentrations in excess of 5 mg/l, the aeration system would be required to be operated continuously between October and April. If the hypolimnetic aeration system was operated to offset the entire rate of oxygen decline (*i.e.* maintaining DO near saturation levels) it is estimated that the average airflow rates would need to be between 7-10 l/s depending on oxygen transfer efficiencies.

Table 2. Predicted monthly airflow rates of a hypolimnetic aeration system in the Maitai Reservoir required to offset the rate of oxygen depletion in the hypolimnion to a dissolved oxygen concentration of no less than 5 mg/L. Rates were calculated based on two oxygen transfer efficiencies, 60% and 92%, based on ranges reported in the literature (Wüest *et al.* 1992; McGinnis 2000). Note that an average hypolimnetic oxygen depletion rate of 0.08840 g/m³/d, calculated over 2013-1015, was used to determine airflow rates.

Parameter	October	November	December	January	February	March	April	Average
Thermocline depth extent (m)	8.65	9.1	10.1	11.3	10.1	10.1	9.4	10.0
Hypolimnetic volume (million m ³)	3.89	1.79	1.57	1.37	1.57	1.57	1.79	1.61
Total DO reduction (kg/d)	257.6	118.4	104.0	90.8	104.1	104.1	118.4	106.6
Total airflow rate- 92% OTE (l/s)	11.2	5.1	4.5	3.9	4.5	4.5	5.1	4.6
Total airflow rate- 60% OTE (l/s)	17.1	7.8	6.9	6.0	6.9	6.9	7.8	7.1

The number of diffuser manifolds that would need to be constructed to ensure aeration occurred over the entire extent of the hypolimnion is difficult to predict. The

number of manifolds required is dependent upon the rate of airflow a diffuser manifold design can accommodate, as well as horizontal mixing patterns of the hypolimnion, which are presently unknown. Nevertheless, we estimate that between 3 and 7 diffuser manifolds could be required. This estimate is based on previous studies overseas (e.g., Burris & Little 1998, McGinnis 2000) and the T-shaped basin of the Maitai Reservoir. Investigation into horizontal water circulation patterns in the basin using long-term deployments of acoustic-Doppler current meters could provide additional information around the number of diffuser manifolds required.

The operation of the hypolimnetic aeration system (e.g. airflow rate, number of diffusers) would probably need to be operated in an adaptive manner. The adaptive management of the system could be informed by continuous dissolved oxygen monitoring at the valve tower location, as well as intermittent profile data collected in other portions of the reservoir basin.

3.2.5. Hypolimnetic aeration system cost estimate (prepared with input from HunterH20)

Summaries of the capital cost estimates for a hypolimnetic aeration system in the Maitai Reservoir are detailed in Table 3. Where applicable, quotations were obtained from suppliers for any major equipment items which included delivery costs to the Nelson area. Much of the remaining costs were generated using costs provided on the aeration destratification system works, and the consultant's cost database for mechanical and process equipment and civil unit rates and quantities.

Table 3. Capital cost estimate of a hypolimnetic aeration system for the Maitai Reservoir. Note costs were provided with input from HunterH20 based in New South Wales, with major capital items being sourced by Australian contractors and equipment suppliers.

Parameter	Variable	Cost
Site preliminaries & general construction		\$ 18 K
Compressor building		\$ 67 K
Compressors		\$ 60 K
Aeration diffusers & associated equipment		\$ 70 K
Air distribution pipework & fittings		\$ 55 K
Electrical works		\$ 302 K
Sub Total		\$ 572 K
Contractor overheads & profit	18%	\$ 103 K
Project management	5%	\$ 29 K
Base Cost		\$ 704 K
Contingency	30%	\$ 211 K
Total Capital		\$ 915 K

No allowance has been made for encountering significant submerged objects when installing the air lines. To reduce the cost of the compressor installation it may be possible to use temporary buildings.

3.2.6. Hypolimnetic aeration operational costs

The monthly stratification data suggest the hypolimnetic aeration will be required to be operated over a six month stratification period. Based on a six month per year usage of the aeration system, the estimated annual operating cost is approximately:

- \$1,320 *per annum* for mechanical maintenance based on 1.0% of capital spend.
- \$2,265 *per annum* for electrical maintenance based on 0.75% of capital spend.
- \$3,808 *per annum* for electrical power based on \$0.18 per kWh

The total operating (power) and maintenance cost is therefore estimated to be \$ 7,393 per annum if operated continuously over six months. Additional allowance will also be required for maintenance of civil structures over the longer term.

3.3. Tributary inflow transfer

Information on hypolimnetic aeration requirements, described previously, was also used to calculate tributary inflow transfer rates required to offset deoxygenation. In this case, calculations only took account of the total mass of oxygen required to be replenished within the hypolimnion. Total transfer volumes required to achieve this mass transfer were calculated based on mean monthly monitoring data of dissolved oxygen concentration in the North Branch tributary (near the inflow delta). This information was then converted to an instantaneous flow transfer rate for the month period. This simple calculation provides an indicative flow requirement for a water transfer system, should it be considered as a potential option.

These calculations were not able to take into account other potential complicating factors, such as plume mixing dynamics within the hypolimnion, or daily fluctuations in temperature and DO that were not accounted for in our instantaneous (day-time) monitoring. These would likely need to be explored further, if this was considered a viable management option for the reservoir.

Based on mass transfer modelling, the rate of water transfer required to offset deoxygenation ranged between 244.4 l/s in October, to 97.3 l/s in March (Table 4). This seasonal variation was driven mostly by changes in the total hypolimnetic volume, and to a lesser extent by variation in dissolved oxygen concentration in tributary water. On average, an instantaneous transfer rate of 129.1 l/s would need to be diverted from the North Branch tributary to offset hypolimnetic deoxygenation occurring in the Reservoir.

Table 4. Predicted mean monthly water transfer rates for a North Branch tributary water diversion required to offset the rate of oxygen depletion in the Maitai Reservoir hypolimnion to no less than 5 mg/L dissolved oxygen concentration. Inflow rate requirements were calculated based on monthly tributary dissolved oxygen concentrations assuming 100% retention of the water plume within the reservoir hypolimnion. Note that an average hypolimnetic oxygen depletion rate of 0.08840 g/m³/d, calculated over 2013–2015, was used to determine oxygenation requirements.

Parameter	October	November	December	January	February	March	April	Average
Thermocline depth extent (m)	8.65	9.1	10.1	11.3	10.1	10.1	9.4	10.0
Hypolimnetic volume (million m ³)	3.89	1.79	1.57	1.37	1.57	1.57	1.79	1.61
Total DO reduction (kg/d)	257.6	118.4	104.0	90.8	104.1	104.1	118.4	106.6
Inflow temperature (°C)	10.7	11.6	13.2	14.2	12.5	11.3	11.2	12.3
Inflow DO (mg/L)	12.2	11.0	10.2	10.2	11.5	12.4	12.5	11.3
Required water transfer rate (l/s)	244.4	124.6	118.7	103.5	105.1	97.3	109.9	129.1

Flow statistics for the Maitai River North Branch have been calculated using a flow relationship determined by Hewitt and Kemp (2004) (North Branch = 0.6892 × South Branch - 21.693). Seven day mean annual low flows (7-d MALF) in the Maitai River subcatchment were calculated at:

- South Branch 7-d MALF (1995-2014) = 161 l/s
- North Branch 7-d MALF = 89 l/s.

Requirements for transfer of North Branch tributary water to offset hypolimnetic deoxygenation were on average 129 l/s, comprising 145% of the 7-d MALF for this tributary. Moreover, water diversion requirements coincide with the summer period in which flows are lowest and ecological effects of abstraction (e.g. temperature increases) are likely to be greatest. As discussed in Beca (2008), the level of investigation required should be matched to the relative in-stream values and the level of abstraction pressure (*i.e.* the degree of hydrological alteration). In cases with high abstraction pressure and/or high in-stream values, more in-depth investigation, including habitat modelling and flushing flow analysis, is warranted. Beca (2008) state that “Abstraction of more than 40% of MALF, or any flow alteration using impoundments would be considered a high degree of hydrological alteration, irrespective of region or source of flow.”

The requirement for such a high rate of abstraction associated with the inflow diversion, often exceeding total flows available in the river, suggests there to be low likelihood for such a diversion to be a practical management option. As a result of this finding, further considerations of capital equipment, construction, and operational costs associated with this option were not pursued.

4. RECOMMENDATIONS

This feasibility study has identified two potential options that could improve water quality issues in the Maitai Reservoir that are associated with hypolimnetic deoxygenation. Both of these options would require construction of hypolimnetic aeration or destratification devices. These could be designed and operated to prevent significant deoxygenation in the reservoir. Both options could feasibly address the extent and rate of deoxygenation, and be scaled to a reservoir of this size and shape. An alternative approach investigated hypolimnetic inflow diversion, but based on initial calculations it does not appear that this could be implemented without seriously compromising environmental flows in the North Branch tributary.

Some of the key advantages and disadvantages of the two feasible options are outlined in Table 5. Possibly the most recognisable advantage from a water management perspective is that hypolimnetic aeration would preserve the cool-water habitat in the reservoir hypolimnion. Preservation of the thermal structure in the reservoir could allow release of cooler water to the downstream river during sensitive periods. Although a destratified (mixed) reservoir could still maintain water temperatures downstream of the Maitai River backfeed within the current consented limits (*i.e.*, < 3 °C change, and < 20 °C) most of the time, it would give less flexibility on operational control. In this context the hypolimnetic aeration option is more appealing.

Table 5. Key advantages and disadvantages of the destratification and hypolimnetic aeration options for addressing water quality problems in the Maitai Reservoir.

Destratification	Hypolimnetic aeration
<p>Advantages</p> <ul style="list-style-type: none"> - well proven technologies - working New Zealand examples (Auckland, Canterbury) - capital equipment readily available -expertise within NZ and Australia 	<p>Advantages</p> <ul style="list-style-type: none"> - proven technologies - cool water habitat preserved for backfeed over summer/autumn - Lower operational expenditure - Lower capital costs (depending on manifold design costs)
<p>Disadvantages</p> <ul style="list-style-type: none"> - homogenisation of reservoir water temperature during summer - potentially higher operational expenditure (if intermittent operation is not effective) - higher overall capital costs 	<p>Disadvantages</p> <ul style="list-style-type: none"> - capital equipment not readily available - diffuser manifold design requiring overseas engineering expertise

While hypolimnetic aeration is recommended, there is presently no New Zealand expertise and engineering experience for designing such systems. Consequently design expertise would likely need to be sought from overseas, particularly to assist with the design of a suitable diffuser manifold. Destratification devices are more likely to be more easily available, and are presently in operation at several reservoirs within New Zealand (e.g. Watercare, Opuha Dam Company).

Costs associated with the two options, are likely to be similar. Both require the construction of compressor and air-transfer systems to a reasonable extent of the reservoir basin. There is greater uncertainty around costs for hypolimnetic aeration because of the difficulties in estimating engineering costs for the diffuser manifolds. It is probable that the costs identified may be in excess of actual costs, as there was uncertainty around whether the equipment could be accommodated (e.g. housing, electrical) by infrastructure presently located at the dam site. Therefore estimates of construction costs are likely to be at a higher end of the actual project costs.

These water management, construction design, and project cost advantages and disadvantages will therefore need to be considered by NCC. Other options being considered by NCC to mitigate downstream effects on the lower Maitai, such as the aeration of the backfeed outflow water, could prove to be more cost-effective approaches.

5. REFERENCES

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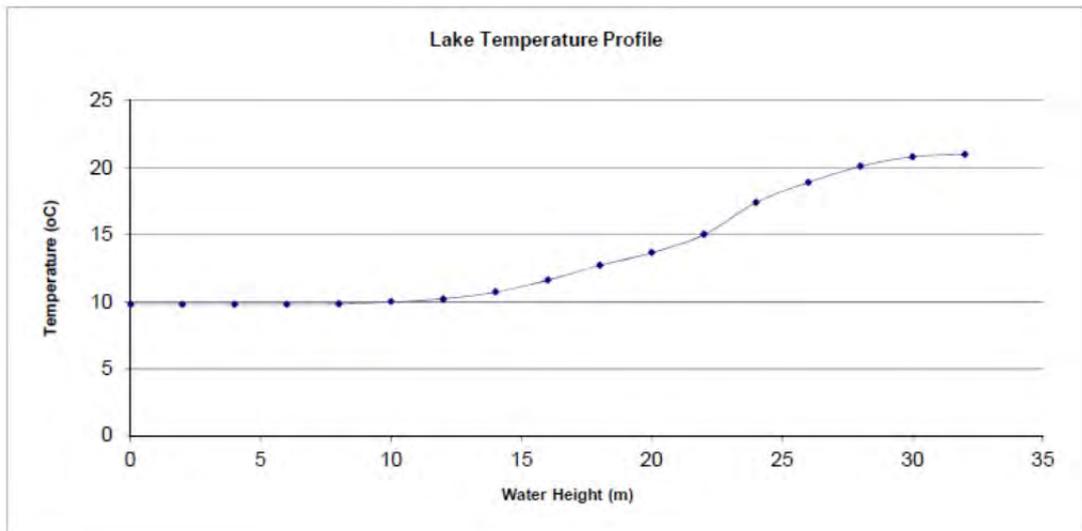
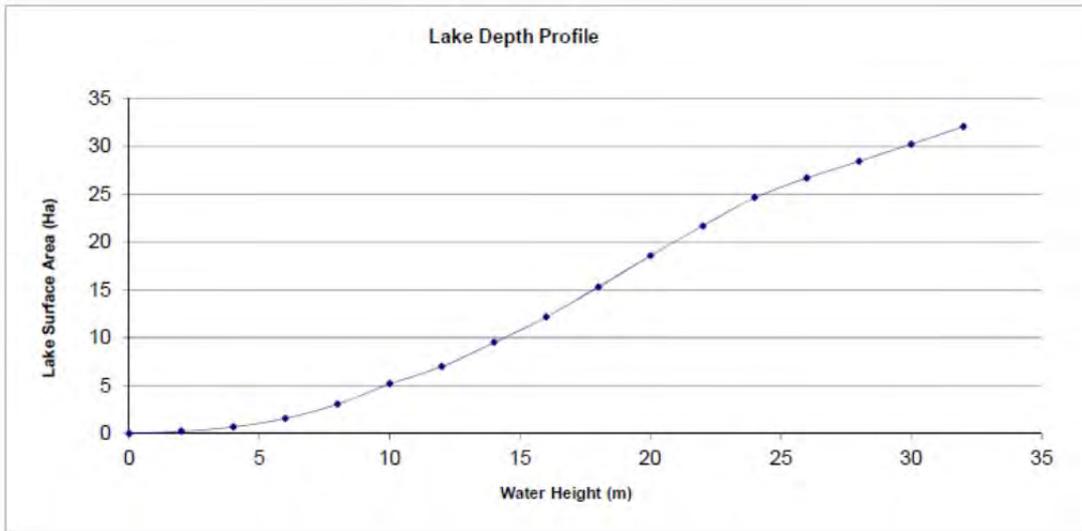
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6. APPENDICES

Appendix A. Model outputs for Maitai Reservoir destratification system design.

Maitai Reservoir																																																																																																																																																
Schladow & Imberger																																																																																																																																																
Atmospheric Pressure Head	h_a	10.2	m																																																																																																																																													
Slip Velocity	V_s	0.3	m/s																																																																																																																																													
Entrainment Coefficient	α	0.083																																																																																																																																														
Dispersion Term	A	0.3																																																																																																																																														
Acceleration Due To Gravity	g	9.81	m/s ²																																																																																																																																													
Water Pressure	P_s	399,267	Pa																																																																																																																																													
Air Pressure	P_a	101,325	Pa																																																																																																																																													
Air Temperature	T_a	18	°C																																																																																																																																													
Air Density	ρ_a	1.212	kg/m ³																																																																																																																																													
Diffuser Depth	h	30.5	m																																																																																																																																													
Maximum Diffuser Length	L_d	160.0	m																																																																																																																																													
Total Pressure Head	H_t	40.7	m																																																																																																																																													
Relative Pressure Head	H_r	0.75																																																																																																																																														
Water Density @ Diffuser	ρ_w	999.720	kg/m ³																																																																																																																																													
Potential Energy (Stratified)	ΔPE	1.56E+08	(kg.m ² /s ²)																																																																																																																																													
Linear Bouyancy Frequency	N_b	0.027	1/rad																																																																																																																																													
Intermediate Quantity	Q_{in}	0.007	S																																																																																																																																													
Intermediate Quantity	Q_{out}	1.77																																																																																																																																														
Intermediate Quantity Ratio	Q_{in}/Q_{out}	243.00																																																																																																																																														
Air Flow @ Diffuser	$Q_{a,d}$	0.00150	m ³ /s																																																																																																																																													
Source Strength	M_s	0.2058																																																																																																																																														
Required Water Flow @ Diffuser	$Q_{r,d}$	1.80	m ³ /s																																																																																																																																													
Solar Bee																																																																																																																																																
Model		585000	3000 gpm																																																																																																																																													
Motor Power			240 W																																																																																																																																													
Area Served			16 ha																																																																																																																																													
Number Required			3																																																																																																																																													
			2.0																																																																																																																																													
Lorenzen & Fast																																																																																																																																																
Evaluation Variable			9.2 m ³ /mm/km ²																																																																																																																																													
Required Flowrate			49.2 L/s																																																																																																																																													
Davis																																																																																																																																																
Time to destratify (Days)		5	12	21																																																																																																																																												
Lake surface area (m ²)		432,000	1,036,800	1,814,400																																																																																																																																												
Lake volume (m ³)		320,670	320,670	320,670																																																																																																																																												
Depth above diffuser pipe (m)		4,422,966	4,422,966	4,422,966																																																																																																																																												
Heat Energy input (J/m ² /day)		30.5	30.5	30.5																																																																																																																																												
Thus R = (MJ)		5	5	5																																																																																																																																												
Wind mixing, W (MJ)		8.01675	19.2402	33.67035																																																																																																																																												
Stability (MJ)		0	0	0																																																																																																																																												
Energy to destratify (MJ)		156.32	156.32	156.32																																																																																																																																												
		164.33	175.56	189.99																																																																																																																																												
Free Air Req (L/s)		54.45	24.24	14.99																																																																																																																																												
Pipe Length (m)		20.5	8.3	4.5																																																																																																																																												
Power (W)		13,917	6,195	3,831																																																																																																																																												
A. Temperature stratification 2013-14																																																																																																																																																
B. Dissolved oxygen stratification 2013-14																																																																																																																																																
Average Airflow Requirements																																																																																																																																																
De-stratification Time	days	50	32	27																																																																																																																																												
Average Flowrate	L/s	5	12	21																																																																																																																																												
Power Required (W)	W	45.0	30.0	25.0																																																																																																																																												
Current Flowrate	L/s	15,336	10,224	6,520																																																																																																																																												
Advised Power Requirement	kW																																																																																																																																															
Your approximate power requirement is 34-40 BHP (25 kW) and you need a 1 stage compressor (3.3 compressions per stage).																																																																																																																																																
We recommend our 4VX compressor for this application (click link to the right). Please call us or e-mail a quote request form if you would like a quotation.																																																																																																																																																
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Appendix B. Breakdown of costs for the Maitai Reservoir destratification system.

Maitai Reservoir Destratification

Concept Design Cost Estimate

1. Preliminaries and establishment		\$18,000	
2. Compressor Building		\$66,340	
3. Compressors		\$159,710	
4. Pipework		\$55,220	
5. Air distribution		\$54,216	
6. Electrical		\$302,025	
Construction Cost Sub-total		\$655,511	A
Contractor Overhead and Profit	18%	\$117,992	B
Likely Contract Sum		\$773,503	C (A+B)
Project Management	5%	\$32,776	D
Likely Project Cost		\$806,279	E (C+D)
Contingency	30%	\$241,884	F
Estimate of Total Costs		\$1,048,162	G (E+F)

ESTIMATE

1. Preliminaries and establishment

NO.	ITEM	UNIT	QTY	RATE	SUB TOTAL	TOTAL	COMMENTS
1.0	Site Establishment / Disestablishment						
	Site preparation	ITEM	1	10,000	10,000		
	site stormwater control	ITEM	1	5,000	5,000		
	signage etc	ITEM	1	3,000	3,000		
						18,000	
					Sub Total	18,000	
	No Contingencies included					0	
	Estimate of Likely Costs				Total	18,000	

ESTIMATE**2. Compressor Building**

NO.	ITEM	UNIT	QTY	RATE	SUB TOTAL	TOTAL	COMMENTS
2.1	Building						
	Steel clad building on raft slab	m2	33	1,000	32,640		
	intake louvres	item	2	3,000	6,000		
	PA and roller door	item	1	2,000	2,000		
	roof ventilation	item	2	500	1,000		
	locks and signage	item	1	1,500	1,500		
	Concrete apron	m2	10	250	2,500		
						45,640	
2.2	Access Ramp						
	earthen ramp	m3	20	100	2,000		
	road base (200mm)	m3	16	100	1,600		
						3,600	
2.3	Compound Fencing						
	Security fence	m	46	350	16,100		
						16,100	
2.6	Services						
	Water	ITEM	1	1,000	1,000		
						1,000	
					Sub Total	66,340	
	No Contingencies included					0	
	Estimate of Likely Costs				Total	66,340	

ESTIMATE

3. Compressors

NO.	ITEM	UNIT	QTY	RATE	SUB TOTAL	TOTAL	COMMENTS
3.1	Compressors						
	15 kW air cooled low pressure hot air screw compressor	item	2	62,000	124,000		
	Transport to site	item	1	15,000	15,000		
	Installation and commissioning	man.day	6	960	5,760		
						144,760	
3.2	Appertenances						
	After cooler	item	2	4,000	8,000		(Price revised to include)
	automatic condensate purge	item	2	800	1,600		(Price revised to include)
	hot air ducting	m	10	100	1,000		
	exhaust in-line fan	item	2	500	1,000		
	outlet valves (SS ball valve)	item	5	400	2,000		DN80
	internal discharge pipework (SS)	m	10	110	1,100		DN80
	Pipework lagging	m	\$10	25	250		
						14,950	
						Sub Total	159,710
	No Contingencies included						0
	Estimate of Likely Costs					Total	159,710

ESTIMATE**4. Pipework**

NO.	ITEM	UNIT	QTY	RATE	SUB TOTAL	TOTAL	COMMENTS
4.1	Pipeline to dam wall						
	Buried pipeline	m	100	95	9,500		DN65 SS
	Pipeline along reservoir wall	m	150	95	14,250		DN65 SS
	Fittings and supports	item	75	30	2,250		SS double saddle
	Bellows/joints	item	4	500	2,000		
	lagging for exposed pipe	m	150	25	3,750		
	condensate blow down tapping and pipe to surface	m	4	200	800		DN25 SS
	condensate blow down valve in surface box	item	2	300	600		
	trenching and installation	man.day	10	960	9,600		
						42,750	
4.2	Pipeline over dam wall						
	Pipeline	m	50	95	4,750		DN65 SS
	saddles	item	40	25	1,000		SS
	chemical anchors	item	80	12	960		
	Installation	man.day	6	960	5,760		
						12,470	
					Sub Total	55,220	
	No Contingencies included					0	
	Estimate of Likely Costs				Total	55,220	

ESTIMATE

5. Air distribution

NO.	ITEM	UNIT	QTY	RATE	SUB TOTAL	TOTAL	COMMENTS
5.1	Distributors						
	DN75 PE100 PN16 Air distribution lines	m	250	9	2,250		
	Fittings	Item	12	80	960		
						3,210	
5.2	Anchors and Floats						
	Concrete Anchor Blocks	Item	105	60	6,300		
	316 SS x 5mm Chain	m	263	19	4,856		
	316 SS Pipe clamps	Item	148	50	7,400		
	Floats	m	105	50	5,250		
						23,806	
5.3	Installation						
	Barge with derrick	day	5	1,000	5,000		
	service boat	day	5	200	1,000		
	Specialist advice to installer	day	2	1,000	2,000		
	installation	man.day	\$20	960	19,200		
						27,200	
					Sub Total	54,216	
	No Contingencies included					0	
	Estimate of Likely Costs				Total	54,216	

Operating Cost Estimate

	Unit	Capital	Opex (\$/mth)	Opex (\$)
Mechanical Maintenance	1.0% capital	364,266		\$ 3,643
Electrical Maintenance	0.75% capital	302,025		\$ 2,265
Power	0.18/kWh		\$ 1,944	\$ 17,496
				\$ 23,404

Compressor Power

Drive size	Number	Utilisation	Hours/ mth	kWh/ mth	\$/ mth
kW	off	decimal			
	15	1	720	10800	\$ 1,944