A review of artificial destratification techniques for cold water pollution mitigation

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UNSW Water Research Laboratory

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1 Introduction

Cold water pollution is a significant environmental issue affecting aquatic ecosystems downstream of reservoirs (Sherman, 2000). Strong thermal gradients cause stratification in reservoirs where surface water temperatures decrease significantly towards the bed (Wetzel, 2001). Reservoirs are often constructed with offtakes that release water from near the bed (Preece, 2004). These releases can subsequently introduce significantly colder water to downstream waterways. Thermal stratification is most common in summer and typically coincides with the release of environmental flows and for irrigation purposes (Preece, 2004). Aquatic biota, including fish in waterways downstream from dams can be negatively impacted by cold water releases (Astles *et al.*, 2003). Many fish species have spawning tolerances and breeding seasons that are linked to changes in river temperature and flow (Boys *et al.*, 2009). Fish are known to exhibit physiological and behavioural variations based on the sudden drop in temperature (Fuiman and Batty, 1997).

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was commissioned by the NSW Department of Primary Industries - Fisheries to complete a literature review of the feasibility of artificial destratification systems to mitigate cold water pollution. This review considers artificial destratification as an alternative solution to retrofitting current dams with multi-level offtakes. The two most commonly applied techniques for artificial destratification in reservoirs are bubble plumes and surface mixer techniques (Pastorok *et al.*, 1982; Sherman, 2000). The advantages, disadvantages and costs of these solutions are discussed, as well as some general considerations for their installation and operation based on standard practice. This review also considers other water quality issues associated with the stratification of reservoirs, including low dissolved oxygen, soluble iron and manganese release and cyanobacteria blooms.

1.1 About this report

This review addresses the theory of stratification, impacts of stratification, options for mitigating these impacts, and the effectiveness of these options in the following sections:

- **Section 2** provides a basic introduction to reservoirs, and natural stratification and destratification cycles due to climatic influence.
- **Section 3** addresses the primary impacts of stratification in reservoirs, including cold water pollution, reduced dissolved oxygen levels, increased iron and manganese concentrations and toxic cyanobacteria dominance.
- **Section 4** addresses the alternative options for mitigating the impacts of natural stratification including multi-level offtakes, bubble plume destratification and surface mixer destratification. This includes the advantages and disadvantages of all three options, and any costing information presented in literature.
- **Section 5** discusses the effectiveness of multi-level offtakes for mitigating the impacts of stratification based on the information presented in Section 3.
- **Section 6** discusses the effectiveness of both artificial destratification systems for mitigating the impacts of stratification. This section introduces the artificial destratification library used in this review.
- **Section 7** summarises the effectiveness of the options discussed.

2 Introduction to reservoirs

Reservoirs are large, artificial waterbodies that are constructed by damming structures that block natural river flows. Reservoirs share similar limnological properties and features to naturally forming lakes (Hayes *et al.*, 2017). Whereas lakes are often categorised based on geological origin, trophic state, thermal regime, or hydrological function (Bengtsson, 2012), reservoirs are often classified based on their purposes (Herschy, 2012). The most common type are storage reservoirs, which are designed to retain large volumes of water for extended periods of time. Dam operators have control over the timing and quantity of releases for the purposes of irrigation, hydroelectricity, water supply and flood control (Poff and Hart, 2002; Herschy, 2012). Reservoirs are often used recreationally, which can affect operation procedures and management protocols (Raman and Arbuckle, 1989; Sherman, 2001).

The trophic state and thermal regimes of reservoirs are influenced by climatic conditions (e.g. solar irradiance, winds etc.) (Miles and West, 2011), as well as their physical properties, such as storage capacity, surface area and depth (Gorham and Boyce, 1989). Understanding the natural thermal stratification and destratification processes of a reservoir is important to effectively mitigate cold water pollution of downstream waterways.

2.1 Natural thermal stratification of reservoirs

Thermal stratification of large waterbodies is a phenomenon that has been recognised, understood and studied for over 50 years (Kittrell, 1965). Stratification is a natural process which affects the vertical temperature and density gradient throughout the water column as a result of external environmental influences and inflows to the reservoir (Ashby and Kennedy, 1993). These factors include direct solar radiation (Huttula, 2012) and increased summer air temperatures (Miles and West, 2011), which warm surface layers, resulting in lower density waters at the top of the reservoir. Stratification is a particular issue for deeper reservoirs, as natural mixing processes (discussed in Section 2.2) are generally not strong enough to overcome stratification through the entire reservoir depth (Gibbs and Howard-Williams, 2018).

Thermal stratification results in the development of zones throughout the water column that are segregated through varying density and temperature regimes (Figure 2.1). From the surface down, these zones are referred to as the epilimnion (surface), the metalimnion (mid) and the hypolimnion (bottom). The metalimnion contains a sharp temperature gradient known as the thermocline, which separates the contrasting warm, lower density waters in the epilimnion and the cold, higher density waters in the hypolimnion (Huttula, 2012). Thermal stratification, in particular the metalimnion, acts as a barrier which limits the natural mixing capabilities of a reservoir (Patterson and Imberger, 1989; Amino, 1990).

2.2 Natural destratification of reservoirs

Reservoirs experience periods of natural destratification, or mixing, through a variety of physical processes. External influences, such as wind turbulence (Dillon *et al.*, 1981) and inflows from catchment runoff or upstream flows (Li *et al.*, 2020) provide mechanical mixing, physically disturbing and mixing water in the reservoir. Cooling of surface layers for short periods at night or extended periods through colder seasons can also induce convective mixing mechanisms (Ashby and Kennedy, 1993; Masunaga and Komuro, 2020).

The response of a reservoir to these natural mixing processes depends on several factors, such as the physical properties of the reservoir (e.g. depth, surface area, etc.) (Kling, 1988; Gorham and Boyce, 1989), and meteorological and climatic influences (Wetzel, 2001). Deeper reservoirs typically take longer to naturally destratify compared to shallow reservoirs. This is mainly due to the degree of thermal stratification and the size (or volume) of the reservoir (Wetzel, 2001).

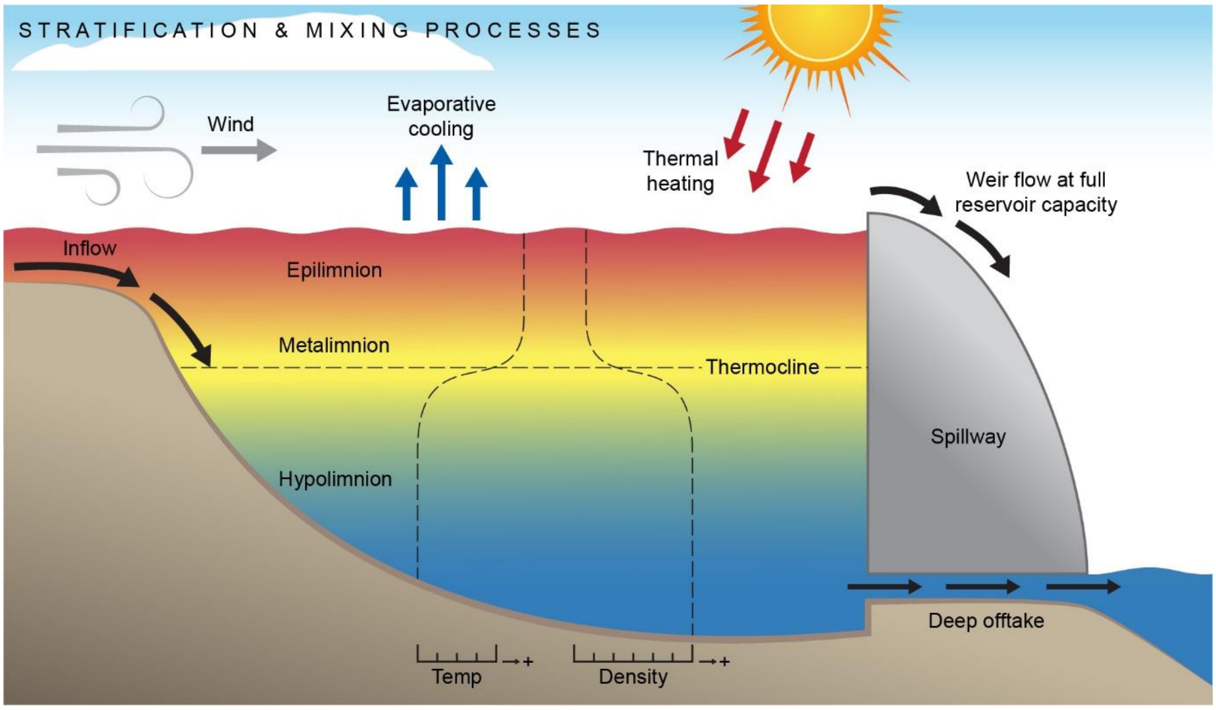

Figure 2.1: Natural thermal stratification and mixing processes in reservoirs

2.3 Artificial destratification of reservoirs

Artificial destratification reverses stratification by means of bubble plumes (e.g Schladow, 1993; Sahoo and Luketina, 2006), surface mixers (e.g. Toetz, 1977; Suter and Kilmore, 1990), or other technologies (e.g. Read *et al.*, 2011). Artificial destratification techniques have been implemented in both Australian reservoirs (McAuliffe and Rosich, 1989; Schladow and Fisher, 1995; Sherman, 2016) and reservoirs globally (Symons *et al.*, 1970; Pastorok *et al.*, 1982; Steinberg and Zimmermann, 1988; Visser *et al.*, 1996) with varying levels of success. As part of this review, a library of current and past artificial destratification systems was constructed (details in Section 6.2).

Section 4 of this review describes the more commonly utilised artificial destratification techniques, while Section 6 reviews the effectiveness of the examples included in the library of destratification systems for mitigating the impacts of stratification in reservoirs.

3 Impacts of stratification in reservoirs

3.1 Cold water pollution

Water released from dams is typically extracted from offtakes located at or near the bottom of reservoirs (Ryan *et al.*, 2001). In a thermally stratified system, releases taken from below the thermocline are significantly colder than the surface waters of the reservoir and downstream waterways (Preece and Jones, 2002; Boys *et al.*, 2009; Miles and West, 2011) (cf. Figure 2.1). These cold water releases (commonly referred to as cold water pollution) can have significant negative impacts on the downstream aquatic environment for hundreds of kilometres (Todd *et al.*, 2005; Lugg and Copeland, 2014) and are considered a major environmental problem (Sherman, 2000).

In Australian reservoirs, thermal stratification in summer can result in 8–12˚C of stratification between the water surface and bed (Harris, 2001), with some deeper reservoirs exceeding 12˚C (Sherman, 2000). Ryan *et al.*, (2001) outlines several environmental issues attributed to cold water pollution, including:

- Significantly lowering summer temperatures in downstream rivers
- Reducing thermal amplitude in streams on a seasonal and daily basis
- Reducing the rapid rise in water temperatures that naturally occur in spring
- Delaying summer temperature peaks by weeks or months
- Sudden and severe temperature drops due to large releases for hydroelectric or irrigation purposes

Perhaps most notable are the significant negative impacts these unnatural temperature variations can have on native fish (e.g., Saltveit *et al.*, 1994; Clarkson *et al.*, 2000; Harris, 2000; Todd *et al.*, 2005). Fish physiology and behaviours are sensitive and responsive to temperature changes in their environment (Fuiman and Batty, 1997). As such, cold water pollution can result in a redistribution of species. For example, Koehn *et al.*, (1995) found significant changes in the fauna composition downstream of Dartmouth Dam (Victoria, Australia) post-dam construction. While changes to environmental flows (i.e. natural river flow prior to construction) would likely have had an impact on the river system and fauna composition, cold water pollution resulted in a significant redistribution from warm-water fish species to cold-water fish species.

Fish reproduction is often linked to annual cycles of temperature variations. Studies have shown that fish growth and metabolism is linked to fluctuations in ambient temperatures (e.g., Jensen *et al.*, 1993; Jobling, 1993; Clarke and Johnston, 1999). Boys *et al.*, (2009) found that native fish species in the Murray Darling Basin have clearly defined breeding seasons and spawning tolerances, which are typically triggered by changes to river flows and water temperatures. Cold water pollution may impact fish reproduction and growth by altering the natural cyclic temperature variations in rivers downstream of reservoirs.

Cold water pollution has been linked to poor recruitment of species (Harris, 2000; Todd *et al.*, 2005), due to sub-optimal conditions for the survival and development of eggs and larvae. Koehn *et al.* (1995) indicated that unsuccessful recruitment of diminished fish species downstream of Dartmouth Dam was, in part, due to cold water releases during breeding seasons. Mortality of fish in river systems downstream of reservoirs has been linked to cold water pollution. Michie *et al.* (2020) demonstrated both the immediate and prolonged mortality effects of 'cold shock' on native Australian fish species. Temperature variations typically observed in stratification gradients were shown to cause mortality across all species.

3.2 Dissolved oxygen depletion

Dissolved oxygen (DO) is an essential part of the reservoir environment, as it contributes to the metabolism of all aerobically respirating organisms. Low dissolved oxygen affects the solubility of many inorganic compounds, the presence of which can threaten water quality in and downstream of reservoirs (Stephens and Imberger, 1993) (see Figure 3.1). In well-mixed reservoirs, a gradual decline in dissolved oxygen at depth can occur as a result of biological oxygen demand (BOD) at the sediment-water interface and throughout the water column (Haynes, 1975). In poorly mixed reservoirs, this gradient in dissolved oxygen increases due to stratification, with a sharp decline observed at the thermocline (Steichen *et al.*, 1979; Miles and West, 2011). Saturated waters from the epilimnion are incapable of penetrating the thermocline due to the strong density gradient, preventing reaeration of the hypolimnion. At the water-sediment interface, biogeochemical reactions deplete available oxygen, resulting in anoxic conditions (Haynes, 1975). These extreme water quality conditions reduce the space in reservoirs in which fish can survive, and can potentially cause fish kills due to increased toxic algae and upwelling of anoxic waters (Müller and Stadelmann, 2004). Gehrke (1988) demonstrated a decrease in heart rate, ventilation rate and metabolic rate in fish at lower dissolved oxygen levels, further exemplifying the impacts dissolved oxygen depletion may have.

To facilitate the continued biological oxygen demand under anoxic conditions, sediments release soluble iron and manganese by reducing metal oxides (Higgins *et al.*, 2007; Beutel *et al.*, 2008; Bryant *et al.*, 2011b) which further impacts water quality (see Section 3.3). Similarly, other nutrients, such as phosphorus and nitrogen, are also released (Beutel *et al.*, 2008), which contribute to algae blooms and cyanobacteria dominance (see Section 3.4).

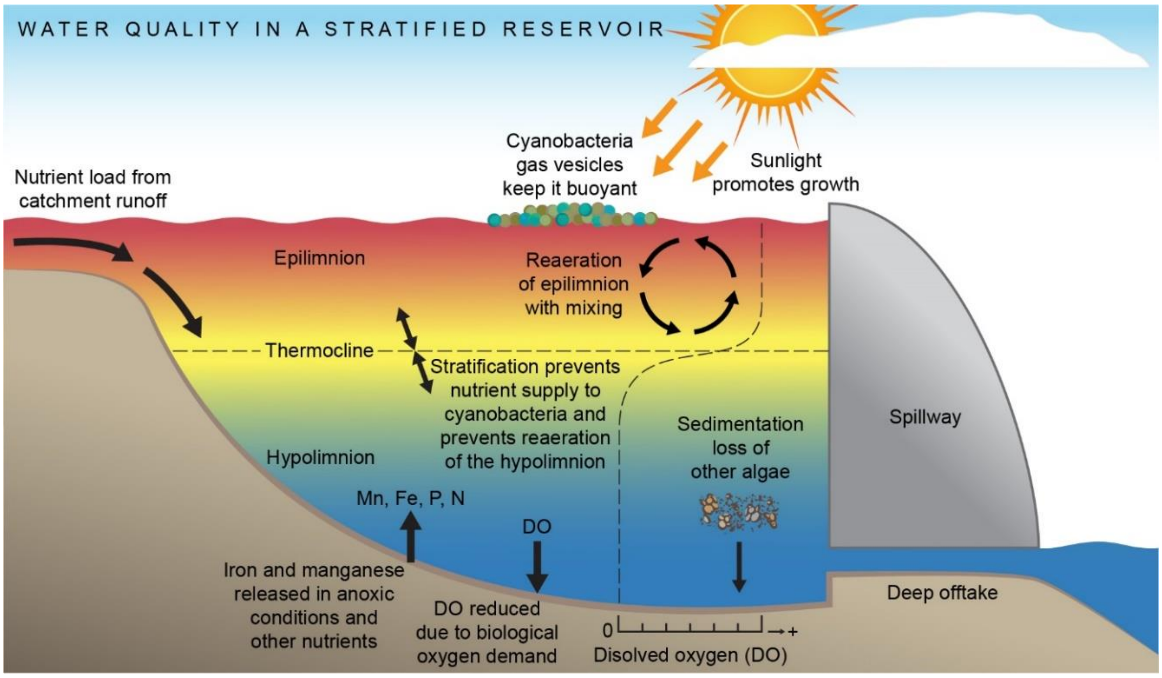

Figure 3.1: Impacts of stratification on water quality in a reservoir

3.3 Iron and manganese

Elevated iron (Fe) and manganese (Mn) concentrations can affect water quality both in a reservoir and following releases to rivers downstream. Iron (Fe) and manganese (Mn) in drinking water can increase turbidity, darken water colour and cause an undesirable taste (Munger *et al.*, 2016; World Health Organisation, 2017) While the human health impacts off Fe and Mn in drinking water are generally minimal, recent studies have found that chronic exposure to elevated Mn concentrations may be linked to learning impairments and other health problems (Wasserman *et al.*, 2006; Bouchard *et al.*, 2007; Khan *et al.*, 2012). Both Fe and Mn can be treated downstream of a reservoir in a treatment plant, however accumulation of these metals generally results in increased treatment costs (Munger *et al.*, 2016).

High Fe and Mn concentrations in aquatic systems may impact fish populations. Several studies have demonstrated significant effects, including oxidative stress (Vieira *et al.*, 2012), gill damage (Hedayati *et al.*, 2014) and haematological impacts (Wepener *et al.*, 1992). Fe and Mn can also pose an issue in irrigation supply water. High concentrations of both metals have been shown to negatively impact crops (Negm and Zeleňáková, 2019), and high concentrations of iron in extraction waters has been attributed to blockages and damage in irrigation equipment (NSW Government Department of Primary Industries, 2014).

3.4 Cyanobacteria (blue-green algae)

Reservoirs are inherently an artificial environment conducive to algal growth. High residence times (Ma *et al.*, 2015) and periods of reduced mixing due to stratification (Spigel and Imberger, 2010) provide favourable conditions for algae growth. Longer periods of residence in surface layers increase photosynthetic processes (Tilzer and Germany, 2010), while stratified eutrophic conditions provide nutrients that promote growth (Bormans *et al.*, 2016).

Toxic cyanobacteria (commonly known as blue-green algae) blooms in reservoirs are of particular concern to poor water quality (Figure 3.1). Cyanobacteria is widely observed to dominate other algal species in reservoirs, especially during periods of stratification (e.g., Toetz, 1977; Burns, 1994). Cyanobacteria are capable of regulating their buoyancy through gas vesicles (Wallace and Hamilton, 1999), which allow them to overcome density gradients in a stratified reservoir and remain at the surface during periods of low wind and high solar irradiance (Visser *et al.*, 1996). This provides a competitive advantage over less toxic, negatively buoyant phytoplankton, such as diatoms and green-algae, by increasing their daily light dose and reducing sedimentation losses (Visser *et al.*, 2016).

Cyanobacteria blooms, and the cyanotoxins they produce, are recognised globally as an issue for reservoir management (Hamilton *et al.*, 2016), in terms of both human and aquatic health (Jöhnk *et al.*, 2008; O'Neil *et al.*, 2012; Ma *et al.*, 2015; Visser *et al.*, 2016; Silva *et al.*, 2020). In drinking water, compounds produced by cyanobacteria can result in an unpleasant taste and odour (Falconer, 1999). Cyanotoxins can impact human health by attacking the liver (hepatotoxins), nervous system (neurotoxins) and skin (dermatoxins) (Hamilton *et al.*, 2013; Merel *et al.*, 2013).

Dam releases containing cyanobacteria can have a significant impact on downstream water quality. Cyanotoxins in irrigation water can affect the growth and development of crop plants (Freitas *et al.*, 2015; Manning and Nobles, 2017). These toxins can also accumulate in plant tissues, and are even capable of persisting in soils post-cultivation (Lee *et al.*, 2017), posing a human health risk. The same toxins that are capable of causing illness in humans can be fatal for fish and other organisms, both in reservoirs and in the downstream environment (Müller and Stadelmann, 2004; Howard, 2012). Around 70% of cyanobacteria blooms are known to release toxins that can be fatal to animals and cause illness in humans (Howard, 2012).

Cyanobacteria blooms, especially in summer where recreational and irrigation use of reservoirs increases, can have significant economic impacts, including lost tourism, drinking water treatment costs and reduced fishing revenues (Lee *et al.*, 2017). Hamilton *et al.* (2013) summarises examples of these economic ramifications, including recreational losses (estimated to exceed over US $1 billion per year in the USA), water treatment costs (up to US $813 million for the USA), water treatment plant closures (with losses exceeding RMB 130 million at Lake Taihu, China), surveillance, monitoring and management of catchment nutrient load costs. The impacts of harmful cyanobacteria blooms are expected to increase with the effects of climate change and land use intensification (Hamilton *et al.*, 2016), highlighting the importance of reservoir management strategies that effectively mitigate their impact on water quality.

4 Mitigating the impacts of stratification

4.1 Preamble

Management techniques are required to mitigate the negative impacts of stratification in reservoirs (cf. Section 2). Importantly, this review concentrates on management strategies aimed at reducing cold water pollution in waterways downstream from reservoirs. Three main management techniques are considered to mitigate the impacts of stratification in reservoirs, including:

- selective withdrawal through multi-level offtakes
- artificial destratification using bubble plumes
- artificial destratification using surface mixers

All three of these are capable of mitigating cold water pollution and other undesirable water quality issues. Conversely, all three have associated drawbacks and costs. Multi-level offtakes are generally downstream focused solutions, and provide little benefit for the reservoir environment itself. Artificial destratification techniques aim to solve the problem at the source, and provide benefits for the in-reservoir environment that then benefit downstream releases.

This section discusses these three mitigating options, the associated advantages, and disadvantages, and provides a summary of installation and operational considerations and costs where available.

4.2 Multi-level offtakes: selective withdrawal

Multi-level offtakes (MLO) are generally downstream focused management solutions and provide little benefit for the reservoir itself. This option enables selective withdrawal from different depths in the reservoir to improve the quality of the release and mitigate downstream environmental impacts of reservoir stratification (Sherman, 2000; Boys *et al.*, 2009) (Figure 4.1). Selective withdrawal can be used to avoid cold, poor quality hypolimnion waters by withdrawing from above the thermocline, and similarly undesirable discharge of toxic cyanobacteria by withdrawing from below the surface (US Army Corps of Engineers, 1986; Preece, 2004). This option is generally considered feasible for dams with an already existing MLO (e.g., Sherman, 2001) as retrofitting these structures may be of considerable cost (Sherman, 2000). Table 4.1 highlights the advantages and disadvantages of multi-level offtakes for mitigating cold water pollution and other water quality issues.

4.2.1 Costs

A retrofit multi-level offtake is widely considered as the highest cost alternative of those options considered in this review (Sherman, 2000; Sherman *et al.*, 2007; Olden and Naiman, 2010). Much of the deterrent to retrofitting dams with MLO structures is this cost, which is almost exclusively contained within the initial capital investment. Construction of a MLO is likely to increase with the size of the reservoir, and further if divers are required (Sherman, 2000). Operational costs are generally minimal compared to initial capital investment, and include the labour and hours required to open and close bulkheads at different levels, as well as ongoing maintenance. Table 4.2 provides estimates for retrofitting dams of a variety of sizes with an MLO. All costs are listed in AUD.

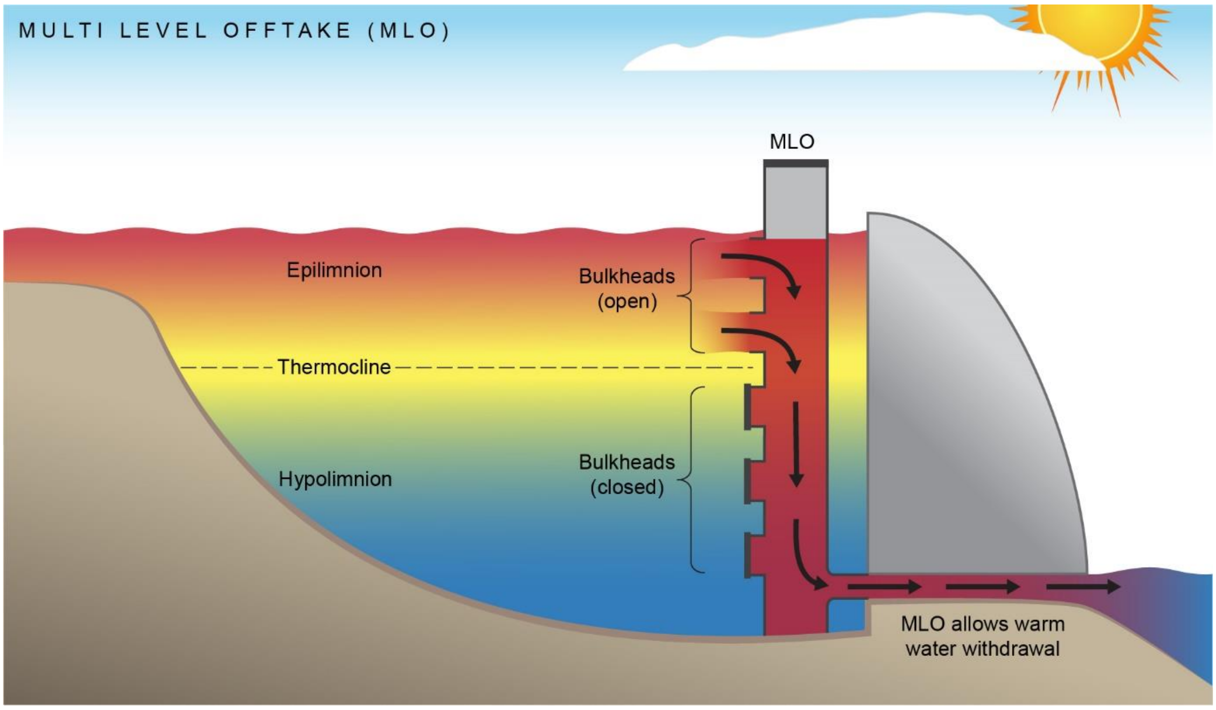

Figure 4.1: Conceptual diagram showing the use of multi-level offtakes in reservoirs

Table 4.1 Advantages and disadvantages of multi-level offtakes.

Advantages	Disadvantages
• Selective withdrawal from warm waters above the thermocline can reduce cold water pollution to the downstream environment (Sherman, 2000). • Selective withdrawal can be utilised to avoid poor quality hypolimnion water. • Selective withdrawal can be utilised to avoid discharging toxic cyanobacteria to the downstream environment, by withdrawing from waters below the surface (Preece, 2004). • Multi-level offtakes could theoretically be operated as a means of restoring environmental flows (Olden and Naiman, 2010). • Selective deep withdrawal could be used to enhance vertical mixing, which may improve the overall quality of water in the reservoir (Li *et al.*, 2018, 2020). • Operationally lower cost than other alternatives.	• Retrofitting a dam with a MLO is considerably more expensive than alternative strategies (Sherman, 2000). For this reason, it is commonly perceived as a high-cost option to mitigating cold water pollution (Sherman *et al.*, 2007; Olden and Naiman, 2010). • Larger withdrawals can result in the entraining and withdrawal of unwanted waters, which may reduce the benefit of the MLO (Boys *et al.*, 2009; Olden and Naiman, 2010). • Withdrawal volumes may be limited by temperature and water quality requirements, given each offtake point is limited to a particular flow rate. • Time and labour are required to move bulkheads to adjust for variations in stratification structure and reservoir levels (Ryan *et al.*, 2001). May require one man-day of labour to adjust (Sherman, 2000). • Maintenance may be complicated and laborious, depending on offtake depths. • Withdrawal from particular layers in a reservoir may deplete waters ideal for fish to live in, and result in fish kills (Higgins *et al.*, 2007).

Table 4.2 Cost of retrofitting reservoirs with a multi-level offtake

Reservoir	Capacity (ML)	Cost (Capital)	Note	Source
Blowering Dam	1,631,000	$26 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Burrendong Dam	1,190,000	$44 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Wyangala Dam	1,218,000	$18 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Keepit Dam	426,000	$18 million	Estimate based on 95% storage capacity	(Sherman, 2000)
Copeton Dam	1,361,000	$53 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Carcoar Dam	36,000	$7 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Shasta Dam	5,400,000	$170 million	Actual cost incurred from retrofitting a MLO	(Sherman, 2000)

Values are converted to 2020 dollars using the World Bank GDP deflator (https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS). Costs provided in currency other than AUD are converted using the World Bank Purchasing Power Parity converter (https://data.worldbank.org/indicator/PA.NUS.PPP).

4.3 Artificial destratification: bubble plumes

Artificial destratification is a widely recognised and utilised strategy for mitigating the impacts of stratification in reservoirs. Rising bubble plumes are the most commonly employed technique of artificial destratification typically due to the perceived low costs (Sherman, 2000) and ability to remedy in-reservoir water quality issues (Ashby and Kennedy, 1993; Visser *et al.*, 1996; Bryant *et al.*, 2011a). These systems involve pumping compressed air through a pipe network to diffusers typically located in the deepest part of a reservoir (Figure 4.2). The air is diffused, often through piping with drilled small holes, into plumes of buoyant bubbles which rise through the water column to the surface. As the plumes rise through the water column to the surface, they entrain cold, dense waters from the hypolimnion to the warmer surface layers. Cold water detrains from the rising plume at the surface, and due to the water density variation, sinks back through the density field to a depth of neutral buoyancy and propagates away from the centre of the plume (Schladow, 1993). This causes local mixing in the vicinity of the bubble plume, dismantling the density structure and breaking thermal stratification (Patterson and Imberger, 1989; Lewis *et al.*, 1991).

Artificial destratification via bubble plumes has been used in many reservoirs globally to mitigate cold water pollution (e.g. Sherman, 2001), prevent cyanobacteria blooms (e.g. Visser *et al.*, 1996), and remediate other water quality issues caused by thermal stratification (e.g. Toetz and Summerfelt, 1972). Varying degrees of success have been noted as part of its application. Further details on different examples of artificial destratification are provided in Section 6.2. Further information on the theory, design and numerical modelling of bubble plumes is provided in (Patterson and Imberger, 1989; Lewis *et al.*, 1991; Schladow, 1992). Specifications on diffuser design, the efficiency of plumes including spacing to optimise interaction between plumes is presented in (Imberger and Asaeda, 1993; Schladow, 1993). Design optimisation of bubble plumes in relation to flowrate and plume spacing is presented in (Yum *et al.*, 2008).

It is important to note the difference between artificial destratification and aeration systems using bubble plumes. Hypolimnetic aeration systems are designed to reaerate the hypolimnion through dissolving bubbles (Mobley, 1997; Li *et al.*, 2019). These systems are specifically designed to have no impact on thermal stratification and are not covered in this review. Table 4.3 highlights the advantages and disadvantages of a bubble plume destratification for mitigating cold water pollution and other water quality issues.

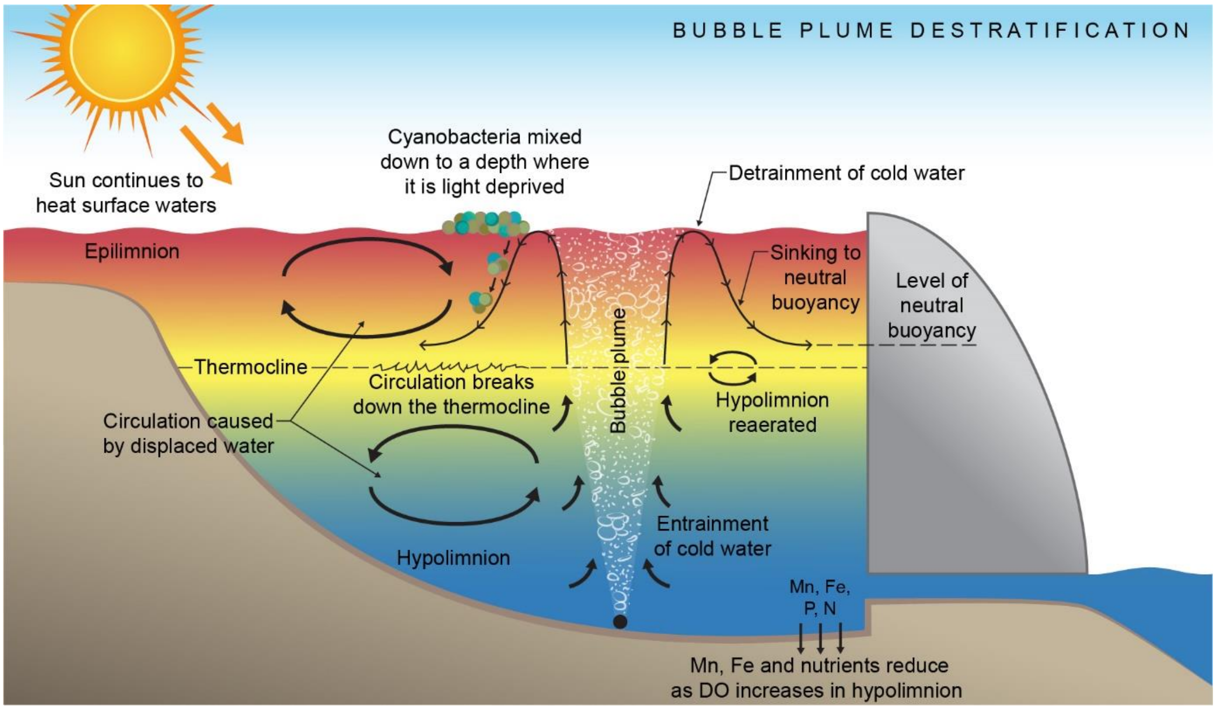

Figure 4.2: Bubble plume destratification in reservoirs

4.3.1 Costs

As previously mentioned, bubble plume destratification is commonly considered to be one of the most cost-effective options for mitigating the impacts of thermal stratification. While the initial capital costs are comparatively lower than those associated with the construction of a MLO, operational costs are generally much higher due to the power consumption of the air compressors used. Reservoir size plays a significant role in the initial and ongoing operational costs of bubble plume destratification (further discussed in Section 6). Larger reservoirs (i.e. deeper and greater storage volumes) typically increase the required operating pressure capacity for compressors and the air-flow rate necessary for effective destratification.

To demonstrate this point, take the costing estimates of a bubble plume destratification system as provided for Chaffey Dam (Sherman, 2001). This literature suggests that, for a reservoir with a storage capacity of 62,000 ML, a flow rate of 1300 L/s is required to provide effective destratification. This system was estimated to cost $2.1 million initially, with an ongoing operation cost of $530,000 p.a. (estimated based on the system in North Pine Dam (Sherman, 2000)). For Burrendong Dam approximately twenty times the size, retrofitting a MLO was estimated to cost $44 million. Assuming a linear increase in costs with reservoir capacity (for demonstrative purposes only), the same bubble plume destratification system would incur ~$10.5 million p.a. Ignoring installation costs altogether, the operational costs of the destratification system would outweigh the construction costs of the MLO in under five years. While this may not directly represent the likely costs, it demonstrates the need for careful assessment (likely requiring theoretical design and modelling) to understand whether optimised bubble plume destratification is in-fact a more cost-effective solution to retrofitting a MLO.

A number of factors affect the installation and operational costs for bubble plume systems, including flow rate, number of diffuser holes, plume spacing, diffuser location, destratification time and the depth and capacity of the reservoir itself. Mechanical efficiency (that is, the efficiency at which the system converts power used by the compressor to a reduction in stratification) is highly dependent on these factors. A peak efficiency of 15% can typically be achieved (Schladow, 1993), however it is not obtained consistently in practice. There is a clear lack of homogeneous design across the systems assessed in this review (see destratification library). In some cases, little to no information about design factors affecting the efficiency of bubble plume systems is provided. Care should be taken when comparing the operational costs for different reservoirs.

Dierberg and Williams (1989) discusses how cost of effective destratification per surface area increases with a decreasing reservoir surface area. While there is no specific information on the design of the systems assessed, the literature suggests that scaling costs may be incurred with oversizing equipment in smaller lakes or disproportionate operation and maintenance costs. This further reflects the potential inconsistencies in the design of bubble plume destratification systems.

Mobley (1997) discusses the costs for the installation and operation of diffuser systems in six reservoirs used for hydropower. These systems differ slightly from a destratification system, as they are designed for hypolimnetic reaeration. Although their costing doesn't specifically relate to a destratification system, the components (e.g. diffuser lines, compressor etc.) and operation (e.g. flow rates, power use etc.) are comparable to that of a bubble plume destratification system. Cost of installation of the diffuser lines and oxygen supply facilities (noting that these systems specifically inject oxygen and not atmospheric air) vary between $600,000 and $2 million.

Table 4.4 provides costing information on existing and planned bubble plume destratification systems. These costs are not necessarily representative of an efficient or successful application of these systems.

Table 4.3 Advantages and disadvantages of bubble plume artificial destratification

Advantages	Disadvantages
• Restore oxygen to anoxic hypolimnion waters by physically mixing saturated surface waters to the bottom of the reservoir (Ashby and Kennedy, 1993; Bryant *et al.*, 2011a; Li *et al.*, 2019). • Inhibit the release of iron, manganese and other nutrients from sediments by restoring oxygen to hypolimnion waters (Toetz and Summerfelt, 1972; Bryant *et al.*, 2011b). • Can be an effective method of controlling cyanobacteria growth. Mixing through the water column eliminates the buoyancy advantage held by cyanobacteria, and reduces growth rates by transporting algae to light-deficient depths (Ashby and Kennedy, 1993; Visser *et al.*, 2016). • Bubble plume destratification attributed to lowering reservoir water pH, which facilities an increase in green algae growth (favourable compared to cyanobacteria) (Pastorok *et al.*, 1982; Cowell *et al.*, 1987) • Proven to be effective in redistributing temperature throughout the water column, increasing deep water temperature in reservoirs and reducing cold water pollution due to withdrawal at deep offtakes (Sahoo and Luketina, 2006; Miles and West, 2011; Helfer, 2012). • Perceived as a low-cost alternative to retrofitting a MLO, based on initial capital investment (Sherman, 2000). However operational cost must be considered in these comparisons. • Destratification can affect an increase in the heat budget of the reservoir, by mixing cold hypolimnion waters to the surface (Haynes, 1975). This can increase the overall efficiency of the system in warming the reservoir and mitigating cold water pollution.	• Circulation of anoxic and nutrient-rich waters to the upper layers of a reservoir can facilitate an increase cyanobacteria and algal blooms by providing them nutrients for growth (Barbiero *et al.*, 1996; Elliott and Swan, 2013). • Toxic cyanobacteria may be mixed to the depth of an offtake that would otherwise avoid it, resulting in a discharge of toxic algae downstream. • Intermittent or insufficient mixing can lead to favourable conditions for cyanobacteria growth (Lewis, 2004; Jöhnk *et al.*, 2008; Visser *et al.*, 2016). • Operational costs increase significantly for larger and deeper reservoirs, due to the volume of water required to be destratified (Sherman, 2000; Ryan *et al.*, 2001). • Limitations may exist for significantly large reservoirs based on power available for the site at which the system is installed. • System maintenance can be difficult, given most of the piping network is usually anchored close to the bed of the reservoir. • Line failures or blockages may be laborious to remediate. Stratification can reinstate quickly, and water quality may be significantly worse than it would have been without the system (McAuliffe and Rosich, 1989). • Rapid destratification can result in oxygen depletion due to mixing of hypolimnetic waters and high BOD sediments. This can result in fish-kills (Pastorok *et al.*, 1982).

Table 4.4 Capital and operational costs of bubble plume destratification systems

Reservoir	Capacity (ML)	Cost (Capital)	Cost (Operational)	Note	Source
North Pine Dam	203,000	$700,000	$180,000 p.a.	Based on a 400 L/s flowrate, which was not successful in mitigating all issues in reservoir	(Sherman, 2000)
Chaffey Dam	62,000	$2.1 million	$530,000 p.a.	Estimate based on system installed at North Pine Dam, for a 1300 L/s flow rate (theoretical flow rate required)	(Sherman, 2001)
Upper Peirce Reservoir	27,800	$3.3 million	$72,000 p.a.		(Sahoo and Luketina, 2006)
Little Bass Reservoir	240	$6,600	$1,100* p.a.	Successful system, using 40 L/s air flow rate	(Burns, 1994)
Candowie Reservoir	2,430	$17,200	$5,700* p.a.		(Burns, 1994)
Running Creek Reservoir	300	$19,500	$11,200* p.a.	System not entirely successful in mitigating issues	(Burns, 1994)
Wombat Reservoir	600	$18,000	$11,200* p.a.	Successful system, intermittent and automatic use	(Burns, 1994)
Tarago Reservoir	38,000	$40,300	$48,900* p.a.		(Burns, 1994)
Cherry Creek Reservoir	17,220	$790,000	$95,900 p.a.	Estimate cost for the installation of a bubble plume destratification system	(Cherry Creek Basin Water Quality Authority, 2004; US Army Corps of Engineers, 2021)

*Literature provides kWh/year, this price is based on an estimate of $0.25/kWh.

Values are converted to 2020 dollars using the World Bank GDP deflator (https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS). Costs provided in currency other than AUD are converted using the World Bank Purchasing Power Parity converter (https://data.worldbank.org/indicator/PA.NUS.PPP).

4.4 Artificial destratification: surface mixer

Artificial destratification can also be achieved using mixers mounted near the surface of the reservoir (Figure 4.3). These systems generally use a raft-mounted impellor located just below the surface of the reservoir to either jet water down (Toetz, 1977; Elliott and Swan, 2013), or draw-up water (Symons *et al.*, 1970; Kirke and El Gezawy, 1997). The impellors are driven by a motor powered directly on the raft or nearby on shore. These systems can be accompanied by a draft tube that extends below the raft to direct the jet to a desired depth (Brookes *et al.*, 2008). Much like bubble plumes, the water entrained responds to the water density variations and rises or sinks to a depth of neutral buoyancy, creating a mixing effect and destratifying temperature gradients in the vicinity of the system.

Surface mixers are most commonly used as a "cost-efficient" alternative to bubble plume destratification systems (Mobley *et al.*, 1995; Elliott and Swan, 2013). There is, however, limited studies (see the destratification library) on the benefits and application of surface mixers when compared to bubble plumes. Table 4.5 highlights the advantages and disadvantages of surface mixers for mitigating cold water pollution and other water quality issues.

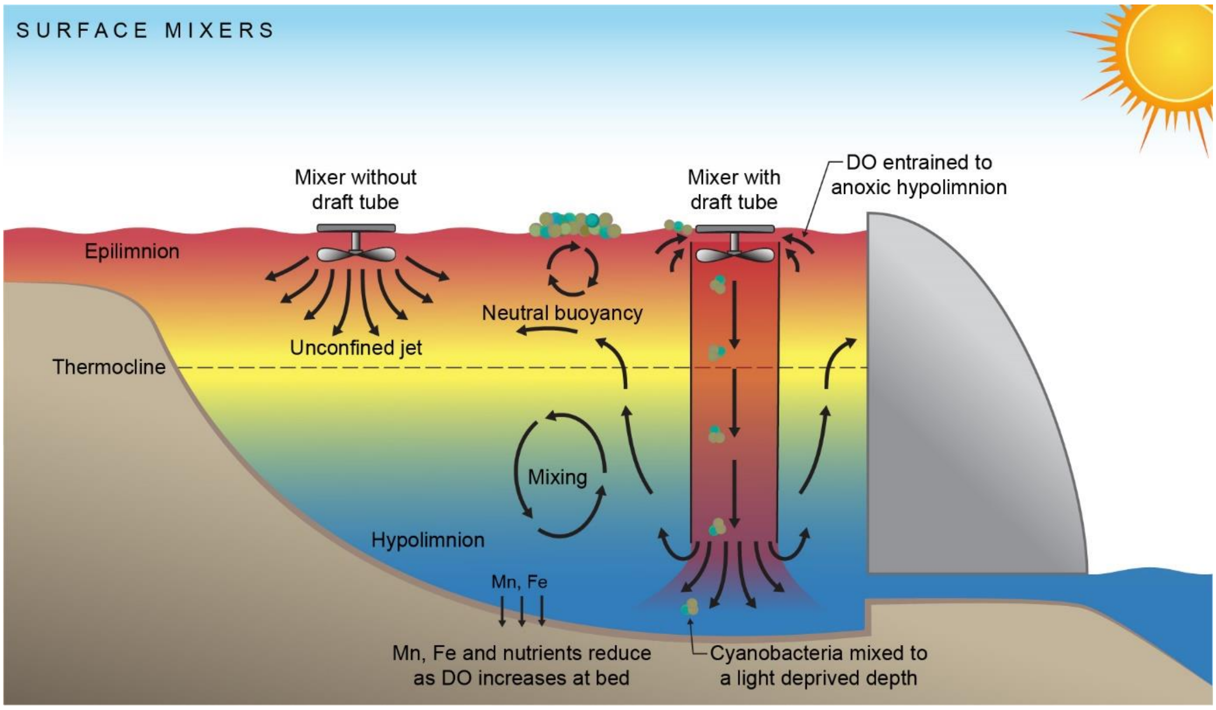

Figure 4.3: Surface mixer destratification in a reservoir with both unconfined and confined flows

4.4.1 Costs

Surface mixers are a low cost alternative to bubble plume destratification due to their lower power consumption and high mechanical efficiency (Kirke and El Gezawy, 1997). There is some information pertaining to the installation and operational costs of surface mixers, however, as with bubble plume destratification, the variability of system designs and purpose make them difficult to compare. Section 6.4 discusses the factors that may influence the effectiveness of surface mixers for artificial destratification. Table 4.6 provides costing information on existing and cost estimates of surface mixer destratification systems.

Table 4.5 Advantages and disadvantages of surface mixer artificial destratification

Advantages	Disadvantages
• Effective method of local destratification. Depending on the goal of the system, a surface mixer may be adequate to mix waters around an offtake, as exemplified in (Mobley *et al.*, 1995). • Maintenance of system likely to be significantly easier than the alternatives, given that most of this system is accessible at the surface of the reservoir. • Draft tubes allow mixing to a desired depth, which can be of benefit in regards to cyanobacteria control. Mixing toxic algae to a specific depth can limit light exposure and inhibit growth.	• Incapable of achieving the 15% mechanical efficiency theoretically possible with bubble plumes (maximum 12%, Stephens and Imberger, 1993b). • Jets that penetrate close to the bed of the reservoir may erode and resuspend bottom sediments (Sherman, 2000). • Can result in localised circulation cells (Lawson and Anderson, 2007), and thus be ineffective for whole-reservoir destratification. • Localised effects may result in negative impacts in other parts of the reservoir (Suter and Kilmore, 1990), e.g. nutrient supply to toxic algae. • Unconfined jets from surface pumps without a draft tube may be ineffective due to kinetic energy lost through turbulence as surrounding water is entrained (Kirke and El Gezawy, 1997). • Modelling of specific reservoirs have shown that surface pumps may provide no benefit to algal control compared to bubble plumes (Antenucci *et al.*, 2001). • Negative effect of suppressing favourable algae species as well as cyanobacteria (Antenucci *et al.*, 2001).

Table 4.6 Capital and operational costs of surface mixer destratification systems

Reservoir	Capacity (ML)	Cost (Capital)	Cost (Operational)	Note	Source
Douglas Dam	1,726,800	$5.8 million	$140,000 p.a.	System installed near dam wall, specifically for mixing discharge waters. Not considered a system effective for destratifying the whole reservoir. Nine total surface mixers used	(Mobley *et al.*, 1995)
Burrendong Dam	1,190,000	< $3.5 million	$155,000 p.a.	Estimate based on TVA systems (e.g. Douglas Dam) for 3 unconfined surface mixers	(Sherman, 2000)
Burrendong Dam	1,190,000	< $3.9 million	$79,000 p.a.	Estimates based on unconfined Burrendong Dam system for five surface mixers with draft tubes	(Sherman, 2000)
Cherry Creek Reservoir	17,220	$975,000	$93,000	Estimate for the installation of 12 surface mixer units	(Cherry Creek Basin Water Quality Authority, 2004; US Army Corps of Engineers, 2021)

Values are converted to 2020 dollars using the World Bank GDP deflator (https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS). Costs provided in currency other than AUD are converted using the World Bank Purchasing Power Parity converter (https://data.worldbank.org/indicator/PA.NUS.PPP).

4.5 Other options not considered in this review

4.5.1 Floating intakes

Floating intakes (or 'trunnions') utilise hinged offtake pipes that allow water to be withdrawn from different depths of the reservoir (Figure 4.4). Feasible pipe diameters generally limit the discharge capacity of these systems. As such, floating intakes are not suitable for irrigation supply storage reservoirs. Their applications are limited in deep reservoirs, as the pipe lengths are general limited to 25–30 m (Sherman, 2000).

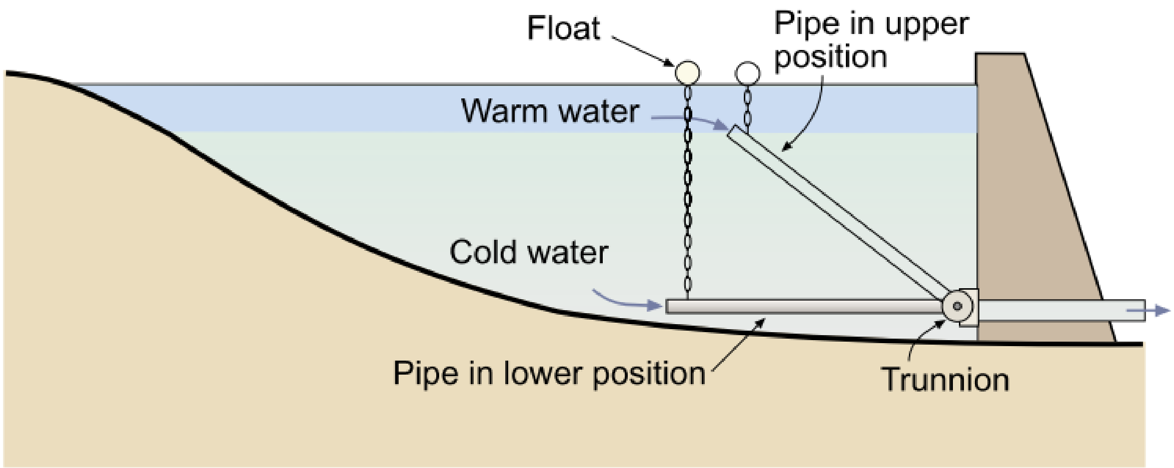

Figure 4.4: Floating intakes (Sherman, 2000)

4.5.2 Suspended curtain

Suspended curtains made of a robust polymer can be suspended or submerged around a dam offtake to mitigate cold water releases. By using material that is relatively impermeable to water, flows are directed either over or under the curtain during downstream release events (Sherman, 2000). By submerging and anchoring a curtain from the bed up, warm surface water can be directed to the offtakes to mitigate cold water pollution downstream (WaterNSW, 2018). Conversely, a curtain may be suspended off the bed of a reservoir and extended upwards of the water surface, with the intention of avoiding the downstream release of toxic algae residing in the surface layers (Watercourse Engineering Inc., 2016).

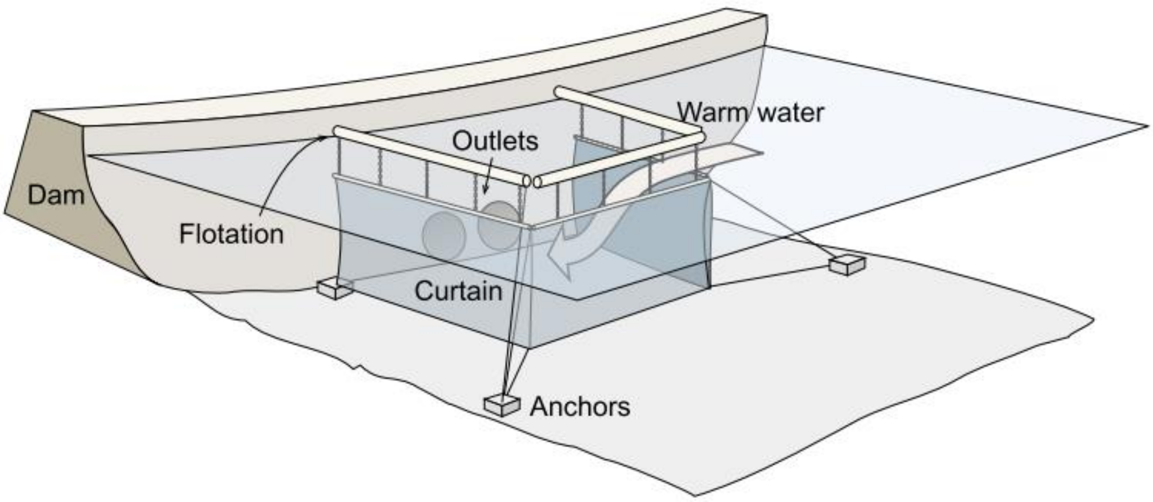

Figure 4.5: Submerged/suspended curtain (Sherman, 2000)

4.5.3 Stilling basin

Stilling basins can be used to prevent cold water pollution mitigation by allowing water to reach an acceptable temperature before discharging downstream. A large, shallow pond is used to collect and retain release waters until thermal equilibrium is reached, at which point the water is discharged. The practicality of stilling basins is limited by reservoir release volumes, as larger releases may require an unfeasibly large stilling basin.

4.5.4 GELI Artificial Destratification

The Gradual Entrainment Lake Inverter (GELI) represents a relatively new iteration of artificial destratification technology, aimed at reducing the power costs of more commonly utilised bubble plumes. GELI makes use of a large, flat disk that ascends vertically through the water column, dragging cold hypolimnetic water in its wake. A shore-based compressor supplies compressed air to an airbladder attached to the disk, providing it with buoyancy. At the surface, the air is released, and the disk sinks back to the bed of the reservoir, dragging with it warm epilimnion water (Read *et al.*, 2011; Smith *et al.*, 2018).

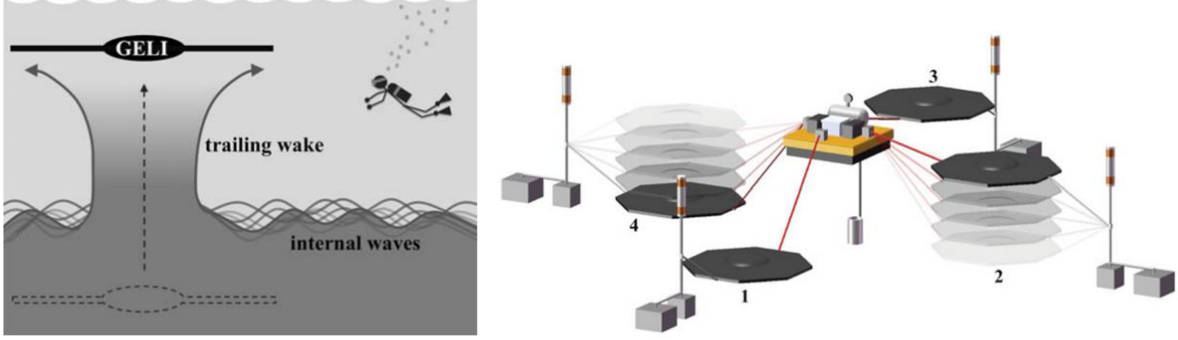

Figure 4.6: GELI destratification technology (Smith *et al.*, 2018)

5 Review of the effectiveness of multi-level offtakes

5.1 Preamble

This section discusses the effectiveness of multi-level offtakes for mitigating the impacts associated with thermal stratification in reservoirs. This desktop assessment of MLO systems is based on the effects on three key criteria, including (i) cold water pollution, (ii) dissolved oxygen, manganese, and iron, and (iii) cyanobacteria. A summary of the considerations for the design and implementation of MLO systems is also provided.

5.2 Cold water pollution

The effectiveness of a multi-level offtake for cold water pollution mitigation is highly dependent on several factors, including the number of offtakes and the depths at which water can be withdrawn. Operational rules would be key to the successful use of a MLO for cold water pollution mitigation, and these should consider factors, such as discharge requirements, reservoir water levels and the temperature profile through the depth of the reservoir near the offtake.

Variations in reservoir levels and thermocline depths are likely to impact the effectiveness of a MLO (Figure 5.1). If the reservoir water levels drops below any of the available offtakes, the options for withdrawal depths that meet downstream temperature requirements become limited. A shallow thermocline can have a similar effect, limiting the number of offtakes that can withdraw from the epilimnion (Preece, 2004). In instances where water levels or intense stratification diminish the effectiveness of a MLO, compromises may be necessary to meet either temperature or discharge requirements. If the discharge volume is a priority, it may be necessary to use offtakes located at or deeper than the thermocline, resulting in downstream cold water pollution. Conversely, if cold water pollution mitigation is a priority, discharge volume may be limited by the number of offtakes drawing from water that meets temperature requirements.

Overall, MLOs are suitable for mitigating downstream cold water pollution, however variations in dam water levels and thermal stratification may reduce the effectiveness of these systems. As such, these systems typically require suitable extraction depths for a given application, as well as well-defined operational strategies.

5.3 Dissolved oxygen, manganese, and iron

As with regulating discharge temperatures, the ability of a MLO to mitigate these water quality issues is dependent on reservoir water levels, degree of stratification and discharge requirements. MLO systems should be designed such that offtakes are located above the thermocline, where water is both DO saturated and low in Mn and Fe concentrations. Offtakes below the thermocline may be required to facilitate larger downstream releases, which will affect the release water quality. As well as this, offtakes above the thermocline may draw poor quality water from below the thermocline, if discharges are large enough (Preece, 2004). Selective withdrawal to benefit the downstream environment provides little to no benefit to the reservoir water quality. Selectively withdrawing from above the thermocline (to benefit downstream) can effectively reduce the volume of quality water within a reservoir (Higgins *et al.*, 2007).

MLOs may be utilised for selective withdrawal of hypolimnion water to promote mixing and benefit the in-reservoir environment, however these strategies will likely negatively impact the downstream environment as a consequence. This management strategy can be employed with an already existing deep offtake, and does not benefit MLO as an effective choice.

5.4 Cyanobacteria

Mitigating transport of cyanobacteria to the downstream environment requires selective withdrawal from below the surface layer of a reservoir (Preece, 2004). The presence of cyanobacteria blooms constrains the number of offtakes that can be used for withdrawal. These constraints are amplified by lower reservoir water levels and can consequently limit desired release volumes. Large releases pose a risk of drawdown from surface layers, and unintentional release of toxic cyanobacteria to the downstream environment.

The benefits of selective withdrawal through a MLO are almost exclusively contained to the downstream environment. Regardless of withdrawal strategy, cyanobacteria is likely to remain a problem in the reservoir itself. Thus, a MLO can only be considered an effective option for avoiding downstream contamination via discharge of toxic algae.

5.5 Lessons learned: considerations for design and operation

It is important to understand how all the aforementioned factors combine to impact how effective or ineffective retrofitting a multi-level offtake might be for a particular dam and reservoir. Effective design of a MLO must consider the competing priorities of in-reservoir and downstream water quality and cold water pollution mitigation. Figure 5.1 highlights some of the potential issues that should be considered as part of the design of an effective MLO.

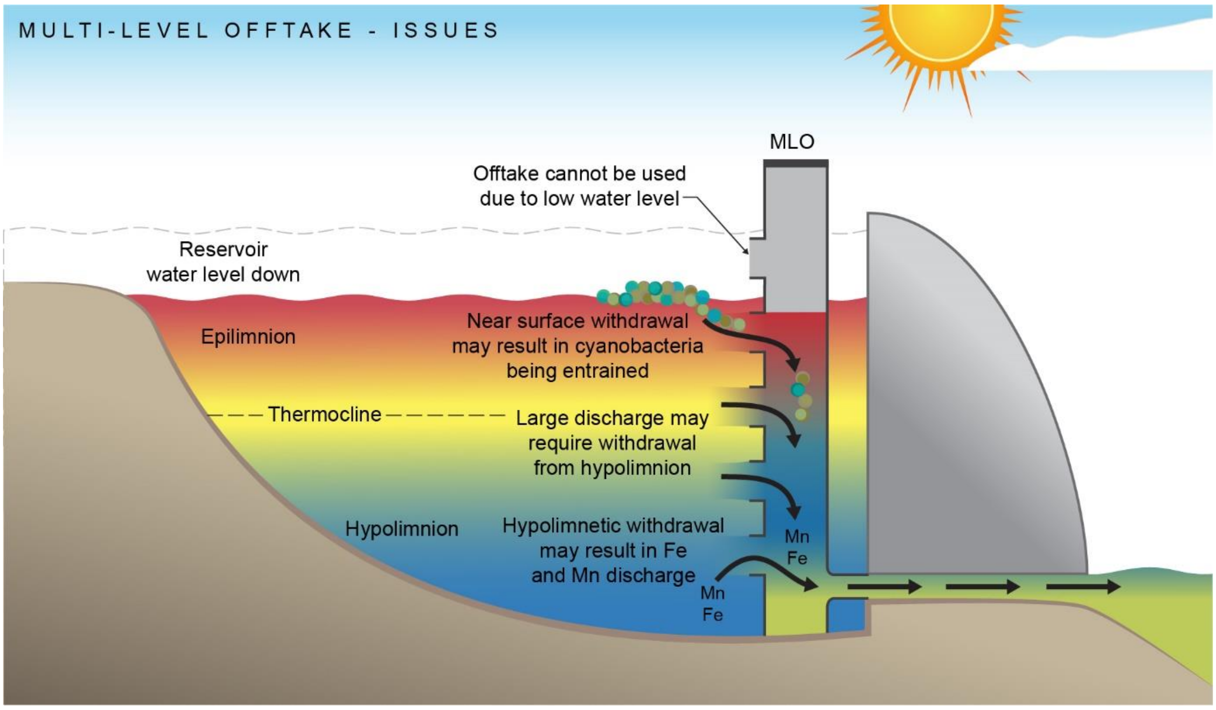

Figure 5.1: Potential issues to be considered with multi-level offtake design

The following are the considerations for the design and operation ascertained from the literature reviewed. These are not to be taken as guidelines, and instead should be an integral part of considering how effective the option of a multi-level offtake might be.

- Cold water pollution mitigation and minimising the release of water with low DO and high Mn and Fe concentrations will likely complement each other as a strategy. These issues are avoided through selective withdrawal from above the thermocline.
- The presence of toxic cyanobacteria blooms in the warm surface layer of the reservoir may limit the effectiveness of a multi-level offtake in reducing cold water pollution (Preece, 2004).
- Withdrawal volume, reservoir water levels and the degree of stratification will significantly impact how effectively a multi-level offtake can be used (Preece, 2004). Reservoir levels may be low enough that one or more offtakes will be unusable. This may be accompanied by strong stratification in the reservoir, resulting in a shallow thermocline. Between these two conditions, the withdrawal layer that meets downstream temperature and water quality requirements is reduced. In this situation, either withdrawal volume or withdrawal quality is a likely compromised. By facilitating volumetric requirements, withdrawal from below the thermocline may be necessary, resulting in cold water pollution and poor quality water release. If cyanobacteria is present in the reservoir, this strategy may result in further contamination of the downstream environment as well (Ingleton *et al.*, 2008). Conversely, if the quality of release water is a priority, there may be significant limitations on the flow rate that can be achieved by a small number of offtakes.
- Large withdrawals may result in the unintentional drawdown or up of poor quality water, resulting in the release of toxic algae and high Mn and Fe concentration water to the downstream environment (Boys *et al.*, 2009).
- The capital cost of retrofitting a multi-level offtake is likely to far outweigh that of installing a bubble plume or surface mixer destratification system. This, however, does not mean that it will be the most expensive option. Operational costs for a multi-level offtake are likely to be much lower than that of a destratification system, and essentially include only maintenance, labour to move bulkheads and design life (Sherman, 2000).
- It may be possible to design a system that automatically moves bulkheads based on a defined set of rules or triggers. This is likely to reduce operational costs but increase capital costs.
- Multi-level offtakes represent a downstream-focussed strategy and provide little to no benefit to the in-reservoir environment. Selectively extracting “good” water from a reservoir can have negative impacts in the reservoir itself, such as a reduction in the liveable environment for aquatic species (Higgins *et al.*, 2007).
- There is room to incorporate effective withdrawal to enhance vertical mixing within the reservoir itself (Li *et al.*, 2018, 2020). This, however, may be limited by other downstream release goals such as particular temperatures or levels of water quality. This may also be possible with an already existing deep offtake.

6 Review of the effectiveness of artificial destratification

6.1 Preamble

This section discusses the effectiveness of bubble plume destratification for mitigating the impacts associated with thermal stratification in reservoirs. This desktop assessment of bubble plume systems is based on the effects on three key criteria, including (i) cold water pollution, (ii) dissolved oxygen, manganese, and iron, and (iii) cyanobacteria. A summary of the considerations for the design and implementation of bubble plume systems is also provided.

6.2 Artificial destratification library

Artificial destratification is used for mitigating the impacts of thermal stratification in reservoirs. Bubble plumes and surface mixers have been applied to reservoirs around the world, with varying degrees of effectiveness. As part of this review, a library of artificial destratification case studies was developed. The library includes, for each reservoir:

- Information on reservoir properties — capacity, surface area, max and mean depth
- Details of the destratification system where available — type (bubble plume or surface mixer), power used, compressor capacity, diffuser design, draft tube length, etc.
- Outcomes of the system regarding breaking thermal stratification, restoring DO levels, reducing iron and manganese and mitigating toxic cyanobacteria blooms
- Any costing information (limited, as most resources were research-based)

The library contains 125 examples of artificial destratification systems. This resource is intended to be available electronically, and thus may be further updated with information based on future work. This information was used to assess the effectiveness of artificial destratification systems for mitigating the impacts of stratification in reservoirs. It is important to consider that the information provided for each system varies, and so it is difficult to definitively compare between cases.

6.3 Bubble plume systems

Bubble plume systems are the most utilised artificial destratification systems. Because of their wide application, there is a significant amount of literature surrounding the detail and effectiveness of these systems. The preference for these systems is typically associated with the perceived low installation and operational costs, however the successful design and operation of these systems has been varied. The majority (80%) of bubble plume systems reviewed refers to reservoirs with a capacity below 100,000 ML. Applications in reservoirs above 100,000 ML have been relatively ineffective at reducing thermal stratification. This may diminish the value of bubble plume destratification as a low-cost alternative, as costs are expected to increase significantly as reservoir size increases. Note that a reservoir storage capacity of 100,000 ML and a mean depth of 15 m has been arbitrarily chosen to assess the effects of reservoir size on the effectiveness of these systems. There is a comparatively smaller sample of case studies demonstrating bubble plume destratification in large reservoirs. As such, it is difficult to make equivalent comparisons for reservoirs above and below these limits.

6.3.1 Cold water pollution

Bubble plume systems are an effective way of mitigating cold water pollution. This review considers breaking thermal stratification as an effective method of reducing cold water pollution, as there is limited literature specifically detailing the effects of artificial destratification on downstream thermal regimes. It was found that 83% were reported to break thermal stratification to some degree. Of these 58% resulted in isothermal conditions throughout the water column. The other 42% either indicated that thermal stratification was reduced but not eliminated, or that the effects were localised and failed to destratify other parts of the reservoir. The majority of systems did not alter the thermal gradients throughout the reservoir were deemed inadequate to either maintain destratified conditions or overcome an existing stratification.

Reservoir size is an important factor in the effectiveness of bubble plume systems. Smaller bubble plume flow rates were shown to be successful in smaller systems (e.g., Starodworskie and Buchanan Lake), however as depth and capacity increases, there was a decline in the success of destratification systems. This was due to insufficient bubble plume flow rates required to break the thermal stratification in the reservoirs. For reservoirs less than 100,000 ML, 57% of destratification systems resulted in full thermal destratification to the depth of the diffusers, whereas 10% failed to have any effect on the thermal stratification. In comparison, 37% of systems in reservoirs of over 100,000 ML capacity failed to have any effect of thermal stratification, with only 21% resulting in full destratification to the depth of the diffusers. Similarly, for reservoirs with a mean depth of less than 15 m, only 13% of systems were found to have no effect, with 49% resulting in full thermal destratification. For a mean depth of 15 m or larger, 29% were found to have no effect, with only 36% resulting in full thermal destratification.

Unsuccessful attempts at thermal destratification in larger reservoirs can, in part, be attributed to poorly or inadequately designed destratification systems. Figure 6.1 represents the success of bubble plume destratification against reservoir capacity and the ratio (as a percentage) between the air flowrate used and reservoir capacity (the “flowrate ratio"). Units of megalitres for reservoir capacity and litres per second for airflow rate were used to calculate the flowrate ratio. The maximum operating capacity was used for the reservoir capacity, as this information was consistently available across most literature.

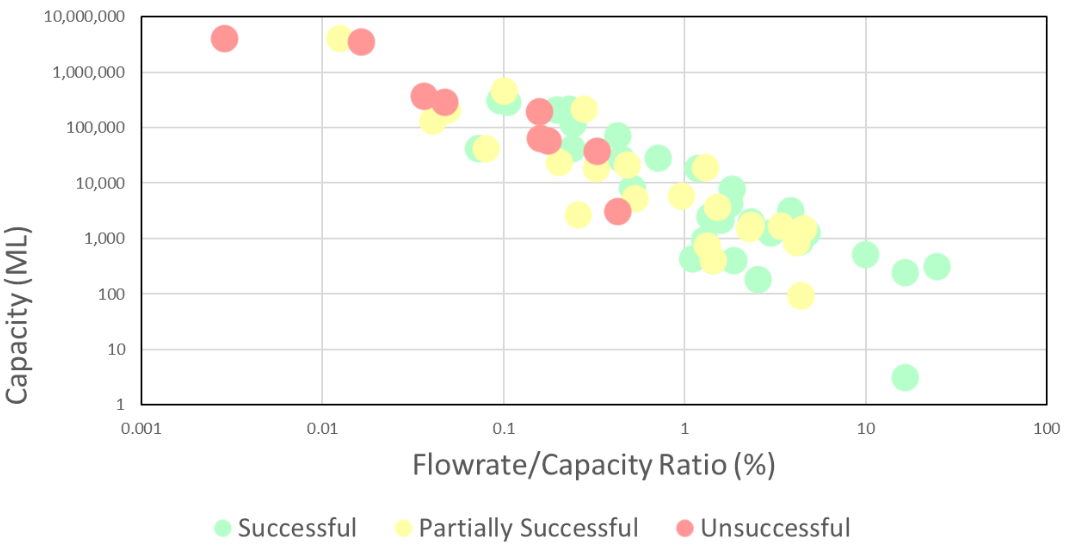

Figure 6.1: Success of bubble plume thermal destratification as a function of reservoir capacity and the ratio of air flowrate to reservoir capacity used

The definition of successful, partially successful, and unsuccessful performance of bubble plumes is discussed in-depth in Section 7.1. In general, successful performance resulted in full thermal destratification of the reservoir to the depth of the diffusers. As reservoir capacity increases and the flowrate ratio decreases, there are fewer examples of successful thermal destratification. There were no reservoirs with unsuccessful performance where the flowrate to reservoir capacity ratio was greater than 1%. As such, this can be considered a first pass estimate for the air flowrate required to effectively mitigate thermal stratification and cold water pollution.

The data for this plot comes directly from the destratification library spreadsheet.

6.3.2 Effectiveness for dissolved oxygen, manganese, and iron

Bubble plume destratification systems have been demonstrated to be an effective tool in managing and remediating water quality issues within reservoirs. Generally, systems effective in thermally destratifying a reservoir are also effective in increasing DO levels and decreasing high Mn and Fe concentrations. Thermal destratification requires mixing of the water column, which results in the oxygenation of anoxic waters which entrain to the surface. An increase in DO is typically accompanied by a decrease in Mn and Fe, as it encourages the microbial reduction of these compounds (Beutel *et al.*, 2008).

For reservoirs where thermal stratification was broken or reduced by a bubble plume system, and DO was measured, 95% reported an increase in DO throughout the water column. Most of these cases reported that issues regarding low DO were eliminated completely, with only 19% indicating that the system was only partially effective (e.g., Tarago Reservoir, where DO stratification remained, despite levels increasing to the depth of the diffuser). In the case of Lake Roberts Reservoir, an unusually high biological oxygen demand was attributed to the decrease in DO, despite the overall thermal destratification.

Similarly, for reservoirs where Fe and Mn concentrations were measured and partial or full thermal destratification was achieved, 88% of cases saw a concentration reduction. Of these, 87% indicated that issues with high Mn and Fe concentrations were eliminated completely. For reservoirs where thermal stratification remained, there were minimal reductions in Mn and Fe concentrations.

As with thermal destratification, past studies have indicated that bubble plume systems become less effective in improving these water quality issues as reservoir size increased. This is likely due to bubble plume systems being inadequately designed to effectively mix the water column. For reservoirs the effects of destratification on water quality was reported, 95% and 86% of reservoirs less than 100,000 ML had some improvements in increasing DO and reducing Mn/Fe, respectively. This reduced to 62% and 58% for reservoirs of 100,000 ML and over. Similarly, 90% and 81% of reservoirs under 15 m mean depth showed some improvements in increasing DO and reducing Mn/Fe, respectively, and reduced to 73% and 64% for reservoirs with a mean depth over 15 m.

6.3.3 Effectiveness for cyanobacteria

The effects of bubble plume destratification on cyanobacteria are significantly more varied. For the most part, the positive effects (i.e. reduction in numbers) on cyanobacteria is noted in conjunction with successful destratification. There are, however, several cases where bubble plume systems either failed to reduce cyanobacteria blooms or resulted in higher numbers, despite effective destratification of the reservoir.

Of the 56 reservoirs where effects of bubble plume destratification on cyanobacteria were assessed, 50% reported a reduction in the number of blooms or a shift in dominance to more favourable species. In most cases, full thermal destratification was reported, demonstrating the link between an adequate system for destratification and positive effects on reducing algal blooms. Conversely, for reservoirs where cyanobacteria remained an issue or increased with artificial destratification, only 31% reported effective thermal destratification. The mean depths of these reservoirs ranged from 11.4 m to 28 m, which indicates that the mixing depth may have affected the effectiveness of these systems in reducing cyanobacteria blooms (e.g., North Pine Dam).

For reservoirs where systems did not provide full thermal destratification, 33% reported a reduction to algae blooms. No systems were demonstrated to reduce algae when they were completely ineffective against thermal stratification.

The complexity of the relationship between successful thermal destratification and cyanobacteria mitigation is apparent when plotting successful mitigation against reservoir capacity and the ratio of air flowrate to reservoir capacity (Figure 6.2). Again, the units used to define the flowrate ratio are megalitres and litres per second for capacity and flowrate respectively. Capacity represents the maximum operating capacity for each reservoir. Cyanobacteria mitigation was considered successful where cyanobacteria issues were either entirely mitigated or reduced to an acceptable level mitigation (discussed in detail in Section 7.3).

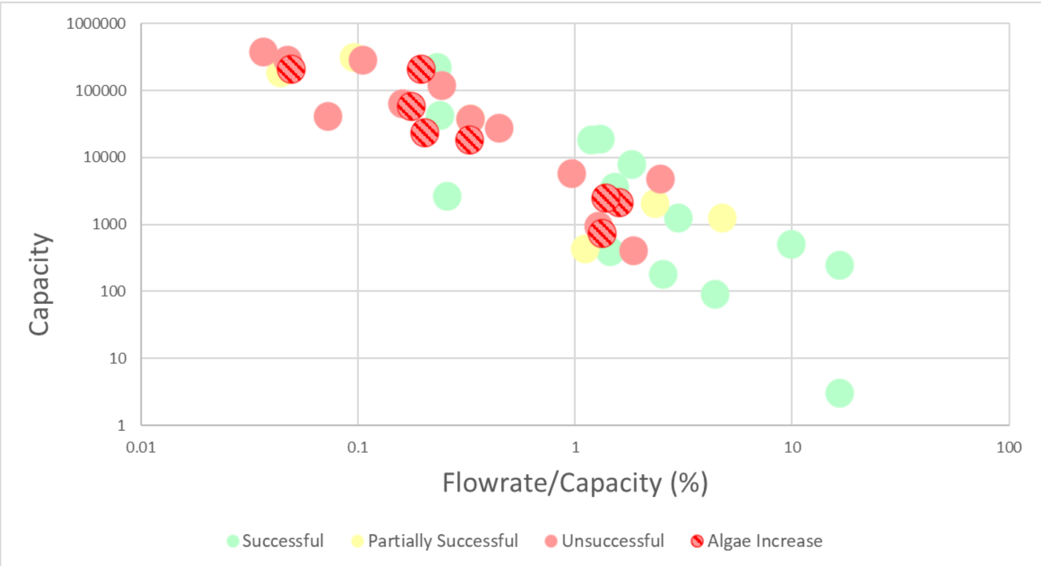

Figure 6.2: Success of bubble plumes to mitigate cyanobacteria as a function of reservoir capacity and the ratio of flowrate to reservoir capacity used

As reservoir capacity increases and the flowrate ratio decreases there were more unsuccessful reservoirs. Unsuccessful attempts either resulted in no change to the pre-destratification cyanobacteria issues or even, in some cases, an increase in growth. This figure follows a similar pattern to that observed with cold water pollution mitigation success (Figure 6.1) and demonstrates the impacts of an inadequately designed system using a flowrate incapable of effectively destratifying the reservoir.

The majority of unsuccessful attempts to mitigate cyanobacteria issues occurred when the flowrate ratio was below 1%. However, there were unsuccessful reservoirs above the 1% flowrate ratio threshold. Discussion of two of these reservoirs specifically noted that lowering water levels over the study period may have impacted algae growth. For the other unsuccessful reservoirs above the 1% ratio, impacting factors included intermittent mixing, microstratification maintaining an anoxic layer and increased external nutrient input over the study period. As with cold water pollution mitigation, the 1% flowrate ratio may be used as a first pass estimate to determine the flowrate required for successful cyanobacteria mitigation but careful consideration should be given to other factors that may influence algae growth.

It is difficult to definitively assess whether bubble plume artificial destratification is an effective method of controlling and reducing undesirable algae in reservoirs. There are several factors that can impact the effectiveness of bubble plume systems, including reservoir size, the capability of the system to completely destratify, operational strategies (e.g., continuous or intermittent operation) and varying external nutrient loads. It is likely that a system will only be effective in reducing cyanobacteria blooms if it is capable of full thermal destratification. However, full destratification is not necessarily indicative of the system's ability to reduce cyanobacteria.

6.3.4 Lessons learned: considerations for design and operation

An overview of the potential issues associated with bubble plume systems used for thermal destratification in reservoirs is provided in Figure 6.3. The design, installation, operation, and cost of these systems is related to several factors, including reservoir size, reservoir type and intended goals of destratification. As such, the following points are not provided as guidelines, rather important considerations in the application of bubble plume systems. These include:

- Warming the hypolimnion may improve cold water pollution issues, while also negatively impacting water quality in the reservoir. At the bed sediment-water interface, warmer temperatures can increase biogeochemical reactions and subsequently biological oxygen demand (Sherman, 2001). These conditions can deplete DO throughout the water column faster than in stratified conditions. It is important to note that a bubble plume system provides adequate mixing such that this increased biological oxygen demand is met.
- In smaller reservoirs, bubble plumes can effectively mitigate cold water pollution. At the same time, there is an increased risk of cyanobacteria blooms due to the inadequate mixing. Conversely, in large reservoirs, bubble plume destratification is less effective due to the size of the mechanical system required to mix greater volumes of water. It is likely that these systems will be much more effective in controlling cyanobacteria in large reservoirs, due to the increased mixing depth.
- Depending on the bathymetry of a reservoir, it may be near-impossible to control cyanobacteria with bubble plume destratification. Where the system may effectively mitigate cold water pollution through thermal destratification, broad expanses of shallow water may allow cyanobacteria to continue dominating surface waters, and even become more of an issue due to the entrained nutrients increasing growth rates (Sherman, 2001).
- Diffusers situated too close to the bed may scour bottom sediments, which then entrain in the rising plume and affect water quality by supplying nutrients to toxic algae at the surface and increasing turbidity (Brosnan and Cooke, 1987; Ryan *et al.*, 2001). As a rule of thumb, at least approx. 1 m should be left between the diffuser and bed.
- For larger reservoirs, where offtakes may not be located close to the bed, strategic placement of diffusers further from the bed to partially destratify the reservoir may be an effective way of reducing costs. This concept has been used successfully in the past (Pastorok *et al.*, 1982; Becker *et al.*, 2006), where reservoirs are mixed to the depth of the diffusers. While this may be beneficial for cold water pollution mitigation, poor quality water may remain an issue below the diffuser depth.

- Destratification should be initiated before the onset of stratification, as breaking strong thermal stratification requires a significantly larger amount of work than simply maintaining it. The bubble plume system, however, should be designed with the capability to overcome the strongest expected stratification. In the event of a diffuser line or compressor malfunction, stratification may quickly re-establish, and thus the system must be able to break a stronger thermal stratification than it would in maintenance conditions. Similarly, for periods of low winds and high solar insolation, stratification potential may be higher (Lewis, 2004), and thus the system may have to do more work to overcome stratification.
- A variable speed drive (VSD) compressor is likely to be a valuable inclusion in one of these systems to adjust flow rates to suit a range of conditions. Adjustments to flow rates will likely affect the mechanical efficiency (Schladow, 1992; Sahoo and Luketina, 2003), which should be taken into account in system and operational strategy design.
- Intermittent use of a system may be an effective way of reducing operational costs for bubble plume destratification (Schladow and Fisher, 1995; Visser *et al.*, 1996). Automated systems have been utilised successfully (Burns, 1994) to initiate bubble plumes when a particular temperature or DO gradient is detected. While this may be a cost effective way of mitigating cold water pollution, it has been demonstrated to negatively impact the state of cyanobacteria in reservoirs (McAuliffe and Rosich, 1989; Visser *et al.*, 1996). Conversely, intermittent mixing can reduce cyanobacteria in reservoirs (Steinberg and Zimmermann, 1988).
- It may be valuable to have variable operational strategies for the purposes of algae control. While either continuous or intermittent operation may be effective in algae control, it has been reported that cyanobacteria was able to reinstate dominance after a number of years of similar operation, by adjusting to the changed density conditions (Steinberg and Zimmermann, 1988). Cyclic use of intermittent and continuous operation may combat the ability for cyanobacteria to adjust. Again, a VSD would be useful for these purposes, given the different flow rates that might be required for each strategy.
- Climatic conditions and variations should be accounted for in system design and operation. Understanding how these conditions (such as wind speed) can affect stratification will allow more effective operation strategies, and thus reduce costs (Li *et al.*, 2020).
- Initial alkalinity and CO_2 level studies may help in understanding the effects destratification will have on algae (Brosnan and Cooke, 1987).
- If cyanobacteria populations are not controlled through bubble plume destratification, the system may cause more harm than good by mixing toxic algae down to a deep offtake that would have otherwise avoided discharging it downstream.
- Bubble plume destratification may increase the negative effects of an inflow event, by lifting nutrients to the surface that would otherwise settle to the bed, thereby promoting algae growth.
- While bubble plume destratification is typically a low-cost option, in large reservoirs the operational costs will increase significantly. There are likely to be huge energy requirements to power compressors capable of delivering the flow rates necessary to destratify large volumes of water.
- Consideration must be given to the power supply of compressors in more remote, large reservoirs. Diverting powerlines should be considered in the cost-benefit of large systems. Large solar power systems may be an attractive option for remote sites requiring destratification.
- There should be consideration given to scenarios where maintenance is required for the submerged pipe network of the destratification system. As this is often anchored to the bed of the reservoir, it can be laborious and complicated to quickly remedy any issues, such as blockages.

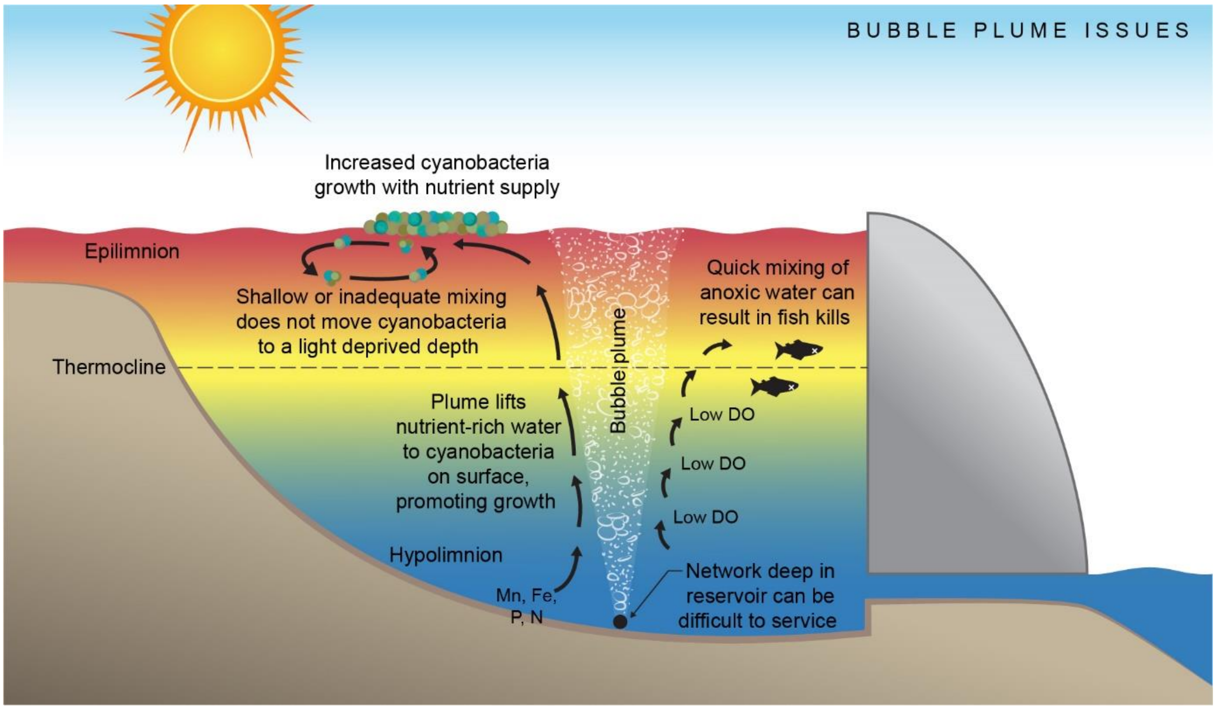

Figure 6.3: Potential issues to be considered with bubble plume design

6.4 Surface mixer destratification

Surface mixers have been used in a much smaller sample of reservoirs, compared to bubble plume systems. The effectiveness of these systems has been varied, however they typically do not perform as well as bubble plumes. This may be an effect of inadequate system design, or the fact that there has been a much larger sample of bubble plume systems to learn from and improve on.

6.4.1 Cold water pollution

It is assumed that the ability for surface mixers to thermally destratify a reservoir reflects their effectiveness in mitigating cold water pollution. Of the 21 surface mixer systems reviewed, only four were noted as inadequate in affecting any change to reservoir thermal stratification. Nine were attributed to at least some change in the thermal regime, and five were reported to be capable of breaking thermal stratification and maintaining destratified conditions (with a temperature gradient of 2°C or less in two of these cases). There was mixed success with both confined flows (draft tube) and unconfined flows. Four of the five systems that reported success with thermally destratifying the reservoir utilised a draft tube to direct flow towards the bed. The only reported successful thermal destratification using an unconfined jet was found in Ham's Lake, one of the smallest reservoirs assessed.

The effectiveness of these systems for cold water pollution mitigation is still not fully understood. With correct design, these systems can be used to effectively create isothermal conditions, however current their application has been limited to smaller reservoirs. For anything other than a very small reservoir, a draft tube is necessary to effectively mix to the bed.

The system in Douglas Dam demonstrates an effective use of surface mixers for improving downstream release through localised mixing. While the unconfined mixers were incapable of destratifying the entire reservoir, they effectively increased discharge temperatures by locally mixing surface waters to the depth of the offtakes.

6.4.2 Dissolved oxygen, manganese and iron

There has been mixed success with using surface mixers to alleviate low DO levels and high Mn and Fe concentrations in stratified reservoirs. Of the 15 cases where the effects on DO were reported, 10 indicated an increase in DO as a result of artificial mixing. Seven of these reported that the systems completely removed issues with low DO in the reservoir. A comparatively smaller number (four) reported the effects on Mn and Fe levels, and for the most part these effects aligned as expected with changes to DO (i.e. decrease in Mn and Fe with an increase in DO). Incomplete mixing at Lake Arbuckle resulted in an increase in total DO, however low DO levels remained below the lowered thermocline, which resulted in an increase in Mn in poorly mixed areas. This highlights the importance for these systems to effectively thermally destratify through the whole water column, if water quality improvement is a priority.

There is a weaker link between thermal destratification and an increase in DO levels, compared to bubble plume system. Of the 15 cases where the effects on DO were reported, 10 reported an expected trend of either reducing thermal stratification and increasing DO, or no change to both. The other five demonstrated uncharacteristic changes of either an increase in DO despite inadequate mixing, or a decrease in DO where thermal stratification was broken to some degree.

It is difficult to definitively discuss how effective these systems can be in alleviating these water quality issues with such few case studies. The use of these systems for localised mixing (as with Douglas Dam) appears to be effective, where DO saturated water pumped to the depth of the offtake improved release water quality. It should be noted that these surface pumps were used in conjunction with hypolimnetic oxygenation, demonstrating a case for using these systems in conjunction with other destratification methods or water quality restoration.

6.4.3 Cyanobacteria

Cyanobacteria suppression is one of the more desired effects of surface mixer destratification, where algae is physically mixed down to a depth at which it is light deprived. Despite this, of the 12 cases that reported effects on cyanobacteria, only five indicated that cyanobacteria issues were eliminated from the reservoir. Studies at Ham’s Lake reported that although cyanobacteria was reduced, there was a significant increase in algae mass observed, which may be undesirable in some reservoirs. The surface mixer system in Myponga Reservoir, in conjunction with a bubble plume system, was capable of reducing cyanobacteria except for a period of high solar insolation and low winds. This system was not adequately designed to break thermal stratification under these conditions and an increase in cyanobacteria was observed.

The effects of confined flow through a draft tube are pronounced when assessing the effects on cyanobacteria. Three cases of unconfined flow reported the effects on algae, all of which were not completely effective. Two of these reported no reduction to cyanobacteria numbers. The third occurred in Ham's Lake, which is a comparatively small body of water and did not require a draft tube for complete mixing. Of the three instances where a draft tube was used and cyanobacteria remained an issue, two pumped water from bed to surface. These systems likely drew nutrients to the surface, promoting algae growth. In both of these cases, full thermal destratification was not achieved, which may be a reflection of the lack of mixing depth required to inhibit algae growth. Conversely, all the cases that reported effective control of cyanobacteria growth utilised a draft tube for confined flow.

The effectiveness of surface mixers to reduce cyanobacteria growth is linked to their effectiveness to thermally destratify a reservoir. In the three instances where cyanobacteria was not affected, the systems were not capable of completely eliminating thermal stratification. In the two instances where an increase in cyanobacteria was observed, the systems had little to no affect on thermal stratification.

6.4.4 Lessons learned: considerations for design and operation

An overview of the potential issues associated with surface mixer systems used for thermal destratification in provided in Figure 6.4. The design, installation, operation, and cost of these systems is related to several factors, including reservoir size, reservoir type and intended goals of destratification. As such, the following points are not provided as guidelines, rather important considerations in the application of surface mixer systems. These include:

- Reservoir size (both large and small) can limit the effectiveness of surface mixer destratification. In small reservoirs, these systems have been ineffective in both improving DO conditions and weakening stratification (Lawson and Anderson, 2007). As well as this, the mixing depth may not be enough to limit algae growth, and artificial mixing may instead promote the growth of cyanobacteria. In deep reservoirs, surface mixers have been ineffective in supressing toxic cyanobacteria.
- Draft tubes are a necessity for surface mixers to be effective. For anything other than a very small, shallow reservoir, an unconfined jet will spread quickly and provide inefficient mixing (Kirke and El Gezawy, 1997).
- For those systems that jet water close to the bed, care must be taken to not scour the reservoir bed. Scouring will increase turbidity and likely reduce water quality by promoting algae growth through nutrient transport to the surface.
- Positive effects of surface mixers appear to be much more localised. These systems are seemingly inadequate for large scale applications, and are likely more beneficial for localised effects such as those demonstrated in (Mobley *et al.*, 1995).
- Bed to surface flows have been ineffective in reducing algae growth. If the system is implemented to supress toxic cyanobacteria, surface to bed flows should be employed.
- Loading from wave action on the surface of the reservoir need to be accounted for in design (Sherman, 2000).
- The effect of water surface fluctuation must be account for in design (Sherman, 2000). If a draft tube is designed to mix water close to the maximum depth of a reservoir, lowered water levels will see the draft tube impacting the bed. It is recommended that draft tube length be adjustable for this purpose.
- In public access reservoirs, caution must be taken to ensure impellor/propellor blades cannot harm reservoir users. There is also a need to protect equipment from vandalism.

- As a standalone solution, surface mixers are unlikely to be an effective solution to mitigating issues with reservoir stratification, especially in larger reservoirs. Instead, they may be effectively used to compliment other management strategies. For example, in conjunction with bubble plume destratification, surface mixers may be able to enhance cyanobacteria suppression and concurrently assist destratification processes.

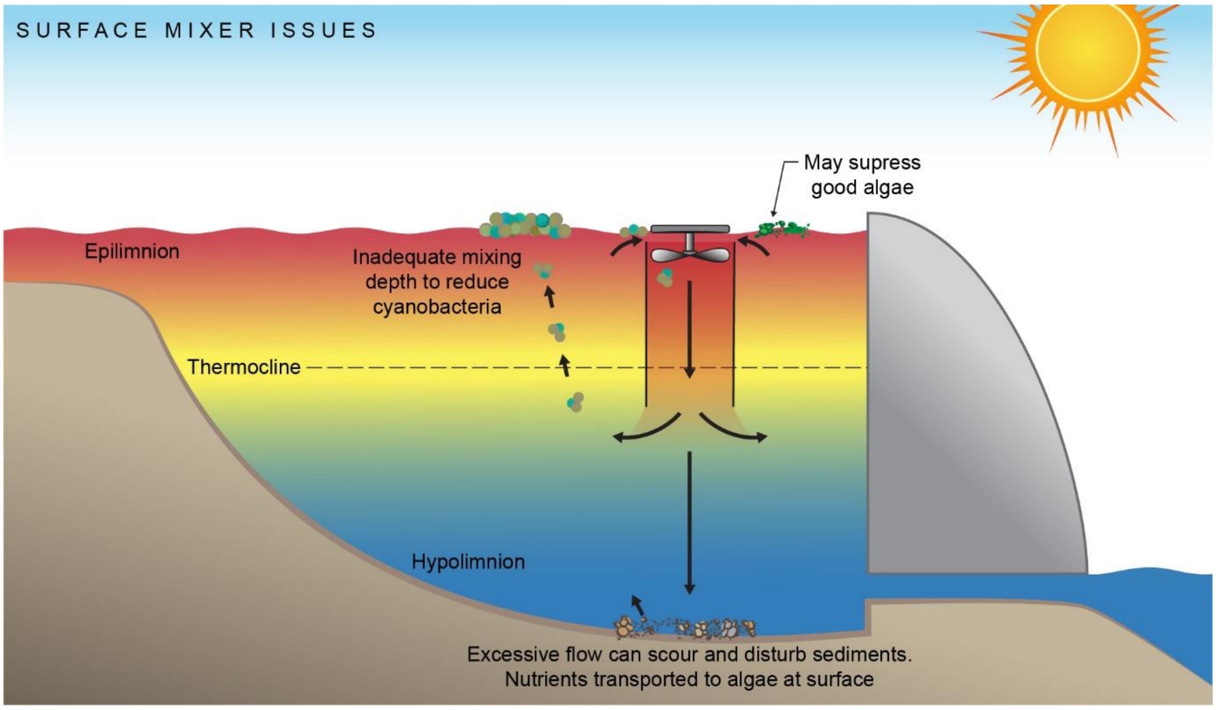

Figure 6.4: Potential issues to be considered with surface mixer design

7 What is success?

A lack of consistent definitions and qualitative discussion used throughout the reviewed literature made it difficult to compare success between reservoirs. Further, data collection on each reservoir was different, so quantitative measures for direct comparison were not available.

This section discusses generalised definitions of success, based on the qualitative information reported in the literature. Where possible, quantitative metrics are discussed, however these should not be considered absolute guidelines. In each study, success was subjectively stated by the reservoir managers and depended upon the desired outcomes. As such, success must be defined separately for each of the desired outcomes.

7.1 Cold water pollution mitigation

The definition of successful cold water pollution mitigation remains an area of study and specific literature focussing on the ecological impacts of cold-water pollution was limited, although we understand research is actively being undertaken.

One method (Sherman, 2000) was to consider the variation in temperature downstream from a reservoir from the "natural" temperature. The temperatures upstream of a reservoir can be considered as a surrogate of the "natural" temperature, so successful mitigation of cold water pollution could be identified by comparison of upstream and downstream temperatures. However, a direct comparison is difficult due to the daily temporal variability and time lags between upstream and downstream created by the reservoir.

Other studies (e.g. Preece and Jones, 2002; Astles *et al.*, 2003) have identified temperature thresholds that affect fish physiology, behaviour and breeding patterns. Mitigating downstream cold water temperatures to remain above these thresholds could be a key consideration in the success of cold water pollution mitigation strategies. Note that these temperature thresholds are the subject of a number of current studies and so have not been quoted in this report.

When a reservoir has an active destratification system, successful cold water pollution mitigation can be defined from the temperature structure within the reservoir. Near-isothermal conditions were commonly defined as being when the surface and the bed temperatures were less than 2˚C different (e.g. Haynes, 1975). If isothermal conditions exist within the reservoir, cold water pollution can be considered successful.

7.2 Dissolved oxygen, iron and manganese

Dissolved oxygen (DO), iron and manganese concentrations are indicative of in-reservoir water quality. An increase in DO and decrease in iron and manganese is a successful measure of a reservoir. Dissolved oxygen, iron and manganese concentrations are closely linked in a reservoir environment, due to the elevated redox potential in a destratified environment (Pastorok *et al.*, 1982). Thus, successful actions to increase dissolved oxygen concentrations will likely result in the successful decrease of iron and manganese concentrations.

In instances where selective withdrawal depths are available, successful DO, iron and manganese strategies might be defined by the minimising of poor-quality extraction water. This will generally involve withdrawing water from above the thermocline, however this becomes intrinsically linked to cyanobacterial management which can prohibit surface water extraction.

When a reservoir has an active destratification system, successful DO, iron and manganese strategies can be defined within reservoir. DO concentrations of less than 5 mg/L at any depth are considered to negatively affect the presence of fish species (Gibbs and Howard-Williams, 2018). Soluble manganese is released at the sediment-water interface when DO is below 5 mg/L and soluble iron is released when DO is less than 2 mg/L. As such, maintaining DO above 5 mg/L throughout the entire reservoir water column can be considered a measure of success.

Examples (Visser et al., 1996) considered successful improvement of water quality when DO was raised consistently above 5 mg/L throughout the water column (homogenous conditions). Similarly, (Ashby and Kennedy, 1993) considered successful water quality with DO concentrations were between 4 and 6 mg/L at the bed and there was a decrease in iron and manganese concentrations.

7.3 Cyanobacteria mitigation

Defining successful cyanobacteria mitigation by reservoir destratification alone is difficult due to the number of external variations including nutrient input and available sunlight.

The Australian Guidelines for Managing Risks in Recreational Water (NHMRC, 2008) outlines quantitative thresholds for potentially harmful levels of blue-green algae. “Green” level alert represents surveillance mode, where levels do not exceed a threshold of 5000 cells/mL of *M. aeruginosa* or a total cyanobacteria biovolume of 0.4 mm^3/L. Successful operation of a destratification system should maintain conditions below these thresholds, such that no additional action is required outside of routine monitoring. Consideration must be given to concentrations at varying depths. Artificial mixing will distribute the normally surface-dominating algae throughout the water column. It is important to understand both the total biovolume or cell count, and variations with depth.

Like DO, success for cyanobacterial management can be measured by the extraction quality or the internal reservoir quality. In instances where selective withdrawal depths are available, successful cyanobacterial strategies can be defined by avoiding release of toxic algae to the downstream environment by withdrawal from below the thermocline. However, this success may result in the unsuccessful release of poor DO, iron and manganese quality water and also result in cold water pollution.

When a reservoir has an active destratification system, two common measures within the reservoir are considered successful in harmful algae mitigation. The first is an overall reduction in phytoplankton biomass (generally determined by measuring chlorophyll *a* concentrations or cells counts) and the second is a shift in dominance from toxic cyanobacteria to less toxic species such as green-algae and diatoms (Visser *et al.*, 1996). More generally though, a system can be considered successful if it results in a reduction of cyanobacteria biomass, and unsuccessful if it has no influence or increases cyanobacteria biomass as a result of operation.

To reduce the cyanobacterial biomass, especially that of buoyancy-regulating cyanobacteria, algae should be mixed throughout the water column to a depth at which it is deprived of light. Below this depth, respiratory losses overcome the photosynthetic growth, theoretically reducing the potential for net growth (Gibbs and Howard-Williams, 2018). For a system to be successful, it should be capable of mixing cyanobacteria deeper than the euphotic depth (depth at which only 1% of light reaches). As a general rule, the thermocline should be more than three times the euphotic depth to mitigate algae growth (Sherman, 2000; Gibbs and Howard-Williams, 2018).

Successful cyanobacterial management could be measured by profiling chlorophyl-a, temperature and light however this was not commonly undertaken in the literature reviewed.

8 Conclusions & recommendations

Cold water pollution is a complex and challenging issue associated with dams and reservoir management. Along with the significant costs associated with the more commonly implemented mitigation techniques, stratification in reservoirs (the root cause of cold water pollution) presents a host of in-reservoir and downstream water quality issues that impeded these techniques' effectiveness. The UNSW Water Research Laboratory has completed an extensive review of the three most common utilised strategies for mitigating cold water pollution, including selective withdrawal through a multi-level offtake structure, and artificial destratification via bubble plumes or mechanical surface mixers. This includes a summary of the advantages and disadvantages of each system, costing information available from literature and a discussion of the considerations that should be made for the design and implementation of each strategy. There are competing design aspects for each option that are considered as part of this review, including their effectiveness to mitigate cold water pollution downstream of the reservoir, alleviate water quality issues associated with stratification (low dissolved oxygen, high manganese and iron concentrations), mitigate the dominance of toxic cyanobacteria in stratified conditions and their associated capital and ongoing operational costs.

Surface mixers are likely to be the least effective option for thermal destratification when considering their overall impact on both the in-reservoir and downstream conditions. Their effects appear localised, and thus may not be feasible as a management strategy for a whole reservoir system. Design limitations increase with reservoir size and depth. Although limited in application, surface mixers may be a useful and cost-effective strategy for localised mixing in a smaller reservoir with a shallow offtake. A network of mixers could be used to pump warm, higher quality water to the offtake depth specifically for release events to improve release temperatures and mitigate issues with poor quality water discharge. It may be possible to use surface mixers to complement other management strategies to, for example, increase cyanobacteria suppression. Surface mixers represent a limited, low capital cost, medium operational cost solution to the issues reviewed.

Bubble plume destratification is the most versatile and successfully implemented strategy for combating the issues of reservoirs stratification. These systems have been used to thermally destratify reservoirs, improve dissolved oxygen conditions throughout the water column, reduce high concentrations of iron and manganese and supress cyanobacteria. Through a wider range of application, these systems have become better understood and optimally designed. There is, however, much room for improvement in both design and operational strategies, given the number of variables that affect their effectiveness. Concerns for bubble plume destratification generally stem from under-designed systems. This can potentially promote cyanobacteria growth by nutrient entrainment to the surface. As well as this, warming bed waters can decrease dissolved oxygen levels by facilitating increased biogeochemical reactions at the sediment-water interface. These systems are associated with lower capital costs, however they remain one of the more operationally expensive options. This is especially true for large, deep reservoirs where a significant amount of power is required to effectively destratify a reservoir. Bubble plumes represent a flexible, low capital cost, high operational cost solution to the issues reviewed. It is highly recommended that systems are modelled and operational strategies optimised before bubble plume destratification is considered, as this may significantly impact their feasibility.

Selective withdrawal through a retrofit multi-level offtake structure is generally regarded as the most expensive of the options reviewed, based on the significantly higher capital costs. In comparing this option to bubble plume destratification, consideration must be given to the life-time costs of both options. It is possible that the significant capital costs incurred with retrofitting a multi-level offtake structure will outcompete the life-time operational costs of a bubble plume system. This is especially true for dams of significant capacity, where bubble plume operational costs are extreme. It is worth considering that the construction costs for a multi-level offtake will increase with reservoir size. It should also be noted that, if the in-reservoir water quality is of any concern, the value of a multi-level offtake is severely decreased. Compared to destratification techniques, multi-level offtakes offer little to no impact mitigation in the reservoir environment itself. An understanding of release volumes and patterns, as well as the conditions in the reservoir, is important in optimising the design of these structures and assessing their value over other options. Retrofitting a multi-level offtake represents an effective but limited, high capital cost, low operational cost option to mitigating the issues review, with a primary focus on cold water pollution mitigation.

Measuring the successfulness of mitigation measures must consider cold water pollution, water quality and cyanobacteria which are often contradictory. However, maintaining a de-stratified water column is one method of achieving success of all parameters.

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