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Scoping Options for Mitigating Cold Water Discharges from Dams

Dr Bradford Sherman

Report to:
Agriculture, Fisheries and Forestry - Australia, NSW Fisheries, CRC for Freshwater Ecology, and NSW Department of Land and Water Conservation as part of the NHT Murray-Darling 2001 FishRehab Program.

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CSIRO Land and Water, Canberra
Consultancy Report 00/21, May 2000

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Abstract

This report reviews the current state of knowledge regarding engineering methods for the mitigation of cold water pollution below dams. Seven techniques are assessed: retrofitting with multi-level outlets; destratification; trunnions; surface pumps; draft tube mixers; submerged curtains; and stilling basins. The theory of operation for each mitigation technique is described, its efficacy at raising discharge temperatures assessed, and capital and operating costs from actual field deployments presented. A comparison of these methods for the specific case of Burrendong Dam, a major dam providing large irrigation and hydropower releases, suggests that draft tube mixers offer the best price:performance ratio for this sort of system. The cost for the mixer system is less than 1/10th that required to retrofit the dam with a multi-level outlet. More generally, there appear to be several economically attractive alternatives to the expensive retrofitting of multi-level outlets to most dams where cold water pollution is a concern.

1 Executive summary

Cold water pollution is believed to be a major environmental problem below most Australian dams and is especially bad below the large dams used to supply water for irrigation. During summer, thermal stratification in these reservoirs typically exceeds 12 °C between the surface and the bottom with hypolimnion (the cold lower region) temperatures scarcely warmer than during winter overturn. Cold water pollution occurs below these dams whenever water is released because these dams were constructed with only a single outlet located near the bottom. The 8-12 °C depression in river temperature from ‘natural’ conditions immediately below of these dams leaves a cold legacy extending many hundreds of kilometres downstream. The Mitta Mitta, Murrumbidgee, Murray, and Macquarie rivers are all significantly affected by cold water pollution.

Unnaturally low temperatures impact on the whole gamut of biological and chemical processes in lakes and rivers. Artificially low temperatures slow metabolic processes in organisms ranging from phytoplankton to benthic invertebrates and fish. Cold water pollution is known to interfere with the feeding, growth, survival and reproduction of Australian native fish.

Through the mid-1990’s, water resource managers assumed that retrofitting dams with multi-level outlet structures was the only feasible approach to mitigating cold water pollution. Such retrofitting was found to be unacceptably expensive for the benefits it accorded.

In this report, I review six alternative cold water pollution mitigation measures:

- Artificial destratification by mechanical mixing of the water column
- Trunnions (Pipes hinged at the outlet so that the free end can be positioned to draw water from different levels in the water column.)
- Surface pumps (Large fan-like propellers that pump warm surface layer water into existing outlets.)
- Draft tube mixers (Similar in operating principle to surface pumps but with the addition of a vertical tube through which the pumped water travels on the way to the outlet.)
- Submerged curtains (Large curtains made of robust, flexible rubber fabric extending upwards from the bottom of the reservoir so that they surround an existing outlet forcing all release water to originate from above the top of the curtain.)
- Stilling basins (Expansive shallow ponds through which discharge passes so that it may warm up by exposure to the sun prior to entering the river.)

The pros and cons of the different strategies and estimates of capital and operating costs are summarised in Table 1. Prices are estimates for Burrendong Reservoir (1678 GL).

For major reservoirs with large irrigation or hydropower releases, draft tube mixers and submerged curtains provide economically attractive alternatives to retrofitting multi-level outlet structures. Both methods are believed to be capable of increasing discharge temperatures by up to 9 °C under typical summer stratified conditions. Draft tube mixers allow the greatest operational flexibility. Both technologies are suitable for reservoirs of any size.

For small-to-medium sized reservoirs, destratification and trunnions may be feasible as well. Trunnions are only capable of carrying relatively small flows such as required for town water supplies. Retrofitting dams with trunnions can be fairly expensive; in many regards the task is similar to retrofitting a dam with a multi-level outlet in that some of the construction must take place underwater. Destratification can increase temperatures relatively quickly, but must be used continuously to prevent potentially toxic sulphide-rich water from being released downstream.

Stilling basins are not feasible due the probable lack of suitably large tracts of land required for satisfactory thermal performance.

No one technology can be recommended as always providing the best price:performance ratio. Site specific characteristics must be taken into account whenever assessing alternative techniques.

A case study was carried out for Burrendong Reservoir. Draft tube mixers were found to provide the best price:performance of all the mitigation methods. A demonstration system capable of delivering the maximum discharge is estimated to cost $2.2m (including $750,000 for contingencies) to construct and roughly $40,000 p.a. to operate. This compares with an estimated cost of $25m to retrofit the dam with a multi-level outlet structure.

Table 1 Summary of cold water pollution mitigation techniques. Costs are estimates for Burrendong reservoir. The annual operating cost does not include replacement at the end of a system's design life. The expected minimum life for all systems is at least 10-20 years. The temperature increase is the expected maximum temperature gain assuming an overall water column temperature change of 10°C.

Method	Capital Cost	Annual Operating Cost	Temp. Increase (°C)	Pros and cons
Destratification	$1.5m	$75k-300k	8	Feasibility decreases with increasing reservoir size. Increased hypolimnion temperature increases oxygen demand, nutrient release, H_2S production if not operated continuously from spring-autumn.
Selective withdrawal Multi-level outlets	$25m	nil	7-9	Most expensive of feasible alternatives. Allows avoidance of surface layer contaminants such as blue-green algae.
Surface pumps Draft tube mixers	$0.75m-1.5m	$40k-60k	5-9	Offers the most operational flexibility including 'do nothing' option. Some concern regarding resuspension of bottom sediments.
Submerged curtain	$3m	unknown, < $30k	9	Suitable when not subjected to strong currents (flood event flows). Very simple, no moving parts - always operates. Some uncertainty regarding maintenance costs.
Trunnions	$0.8m	nil	9	Not suitable for discharges > 100 ML / d. Deeper reservoirs may require multiple trunions and a multi-level outlet.
Stilling basins				Not feasible due to space and cost constraints.

2 The problem

For many years now, the unseasonably cold water released from stratified reservoirs to satisfy the demand for irrigation and town water supplies has been known to interfere with the natural behaviour of Australian native fish. Because fish are cold-blooded, virtually all aspects of their reproduction, feeding, growth, and survival are highly sensitive to temperature (Harris 1997; Astles et al. 2000); each improves with increasing temperature under natural conditions. Spawning will not occur unless certain threshold temperatures are met. Australian native fish species are adapted to warm conditions and are placed at a competitive disadvantage to alien cold water species such as trout when river temperatures fall below the levels required for successful growth, migration, and recruitment.

The damage from cold water pollution isn't restricted to the native fish population alone. All biological metabolic processes in aquatic habitats slow down as temperature decreases (Astles et al. 2000). Cold water pollution decreases aquatic respiration and invertebrate productivity. This displaces a river's ecology from its natural state even further.

A typical thermally stratified Australian reservoir has an 8-14 °C temperature difference between the surface mixed layer and the hypolimnion during summer. Because most Australian dams were constructed with only a bottom outlet, they cannot conveniently deliver water from the warmer surface layer. Instead, cold and often anoxic hypolimnetic water is released, sometimes with disastrous consequences for native fish. In addition to decreasing summer river temperatures by 8-10 °C, dam releases also may raise the winter river temperature by up to 5 °C. The overall effect is a significant reduction in both the annual temperature range and the temperature rise that occurs during spring as well as a disruption of the synchronism between water temperature and other environmental cues such as day length and hydrology.

In addition to being very cold, bottom water releases from dams may be supersaturated with dissolved gases. This can lead to problems such as gas bubble trauma in fish immediately downstream of the dam as the dissolved gases come out of solution in the fish's blood due to the reduced hydrostatic pressure. The resulting bubbles that form in the fish's blood may block or even rupture blood vessels. Several authors have commented on nitrogen bubble sickness in fish and outlet designs to minimise the problem (Fast 1979; Ruane et al. 1986; Hall 1986a, 1986c). Furthermore, deep water releases often contain high levels of toxic redox products such as hydrogen sulphide that often cause fish kills. Mitigation of hydrogen sulphide poisoning has been the motivation for the deployment of surface pump (described below) and oxygenation systems at a number of reservoirs in the United States that I have visited.

Berkes (1981) has discussed the difficulty of designing large-scale projects to comply with environmental objectives, especially when there is a lack of baseline data. The lack of environmental data often leads to shorter-term economic arguments driving the decision to proceed with a project. Because most large dams generate electricity from their releases, any reduction in flow through the turbines to satisfy environmental objectives incurs a cost in the form of foregone revenue due to decreased electricity sales. The ease and accuracy with which the costs associated with environmental flows can be computed loom in stark contrast to the much harder to quantify intrinsic benefits of maintaining a more 'natural' riverine environment. There is, therefore, a high level of interest, both overseas and in Australia, in developing techniques to cost-effectively combat thermal pollution in reservoir releases while simultaneously maximising hydropower generation and water available for irrigation.

3 Implications for native fish

The impact of the suppression of river temperature on Australian fish has been dramatic (Harris 1997; Lugg 1999; Astles et al. 2000). For example, trout cod, Murray cod and Macquarie perch were completely lost from the Mitta Mitta River downstream of Dartmouth Dam twelve years after the dam commenced operation (Koehn et al. 1995). Recent research by NSW Fisheries at Burrendong Dam demonstrated greatly improved survival and growth of silver perch when water temperature was increased by 6-10 °C (Astles et al. 2000).

The temperature of dam releases is also an important issue overseas. In the USA, maintenance of cold discharge temperatures is generally sought after because of the important salmonid fishery although there is concern about the effect of cold discharges on non-salmonid native fish. An interesting example is the current debate about the benefits of raising discharge temperatures below Glen Canyon Dam to improve habitat for the native humpback chub in the Colorado River. There is a lack of consensus amongst fish biologists as to the ultimate benefit of raising the discharge temperature below the dam. Although the benefits of warmer water temperature to the humpback chub are not contested, some fisheries researchers are concerned that raising the river temperature will allow upstream migration of invasive, non-native fish from Lake Mead and that these fish may out-compete the chub throughout much of its present range in the river. Clearly, it is imperative to consider the effect of modified discharge temperatures on the overall ecological functioning of a river and not just its effect on target organisms.

4 Australian management interest in the problem

Concerns about cold water pollution (CWP) have been raised by NSW Fisheries researchers since at least 1980 (Walker 1980). Despite these early warnings, CWP does not appear to have received formal management attention until 1996 when CWP was first cited as an issue in New South Wales storages by Al-Talib et al. (1996) and a value management study on release water quality was conducted by the Department of Public Works and Services (1996a). At a recent reservoir managers workshop held in Canberra, cold discharge mitigation was identified by participants as a significant issue.

In Victoria, DNRE has studied the impact of CWP on the fish and macroinvertebrates downstream of the Dartmouth Dam (Koehn et al. 1995). Concern about CWP below Dartmouth Dam led to an unsuccessful attempt to destratify the dam during the mid-late 1980's. In addition to the usual fishery concerns, Goulburn-Murray Water have prepared an internal report on the impact of CWP on agricultural productivity (D. Jeffery, pers. comm.).

To date, expensive retrofitting of dams with multi-level outlet structures (MLO) appears to be the most seriously considered option. Other options have been dismissed for various reasons (Department of Public Works and Services 1996b). Trunnions (see below) are structurally limited to smaller sizes unsuitable to large irrigation releases. Public safety concerns have been mentioned as an argument against the use of surface mixers (see below) deployed in publicly accessible waters for reservoir destratification (B. Hindmarsh, pers. comm.) which could be accomplished using alternative methods such as bubble plumes. Syphons have the disadvantage that water bypasses the hydropower plants and so potential electric generation revenue is lost. Syphons are also incapable of delivering water over a rise of 10 m because this would produce a pure vacuum stopping any flow. In many cases the tops of dams are more than 10 m above the full surface level. Because the high cost of retrofitting dams with MLOs typically has been viewed as exceeding any environmental benefits, little progress towards mitigating CWP has been made over the past 15 years.

However, interest in CWP mitigation is on the increase. Following the unsuccessful attempts at destratification during the late 1980's, Goulburn-Murray Water has recently undertaken several internal studies on the feasibility of retrofitting Dartmouth Dam with a MLO structure and in 1997 an internal report was prepared. In addition, Goulburn-Murray Water is in the process of commissioning another scoping study on retrofitting a multi-level outlet that includes both engineering and environmental considerations (D. Jeffery, pers. comm.). Given the large geographical extent of CWP (Cantlon and Blanch 1999), it appears that now is the time to revisit the possible alternative approaches to increasing the temperature of dam releases.

5 Literature review

A survey of Water Resource Abstracts published during the last 30 years yielded few reports or articles directly concerned with cold water pollution. Price and Johnson (1986) identify cold water pollution as a problem at Lake Greeson, Arkansas, and then go on to discuss possible remediation strategies. The paucity of reports on cold water pollution no doubt reflects the fact that most of the literature originates from warm temperate regions in the northern hemisphere where the principle concern is warm thermal pollution creating unacceptable conditions for coldwater salmonids. The lack of direct studies should not be considered a major obstacle to the goals of this report, however, as the underlying principles of thermal pollution are the same regardless of whether one wishes for warmer or colder water to be released from dams. The main limitation here is that we must assume – quite reasonably – that increasing the temperature downstream of dams will produce the desired results or at least move the system in the desired direction. Although there is no direct evidence from the literature to support this contention, it follows logically from the results of Astles et al. (2000).

Because the principle aim of this report is to review and assess the various engineering options for combatting cold water pollution only a brief review of the biological consequences of CWP has been presented. The remainder of the report focuses on the engineering and financial issues associated with different mitigation strategies.

5.1 Realistic expectations – river heat budget

A section of river is considered to be thermally polluted if its temperature falls outside some range usually defined by the temperatures of unregulated rivers in the catchment upstream. Using such a criterion, Lugg (1999) estimated that nearly 3000 km of inland rivers are affected by cold water pollution with 400 km reaches of both the Murrumbidgee below Burrinjuck Dam and the Macquarie R. below Burrendong the worst affected. In general, one must be cautious in making such comparative assessments because of confounding factors such as local variations in climate and differences in river discharge and average depth.

To make a realistic assessment of the potential habitat improvement resulting from increased discharge temperatures, we need to consider the heat budget of a river as it flows downstream. The temperature at a downstream location in a river, $T_{D/S}$, depends on the river temperature upstream, $T_{U/S}$, and the amount of heat gained or lost by direct solar heating (Q_{solar}), evaporation ($Q_{evaporation}$), conduction ($Q_{conduction}$) and longwave radiation ($Q_{longwave}$) during the time interval Δt taken by the river to travel between the two locations. Here, A and V are the

$$T_{D/S} = T_{U/S} + \left(Q_{solar} + Q_{conduction} + Q_{evaporation} + Q_{longwave} \right) \frac{A}{V \rho c_p} \Delta t$$

surface area and volume of a parcel of water with density ρ and heat capacity c_p.

For a rectangular channel $A / V = 1 / H$ where H is the depth of the water column and the rate of temperature increase varies inversely with depth.

The evaporative and longwave heat fluxes are virtually always negative, i.e. they represent heat lost from the river, whereas Q_{solar} is always positive. The time interval, Δt, depends on a number of hydraulic factors including: channel dimensions, discharge, and bed slope.

Under some circumstances (e.g. turbid, slow flowing water or when deep pools are present) the water column of a river may be thermally stratified. Stratification often occurs when weirs are present on low-gradient rivers such as the lower Darling and the lower Murrumbidgee. Long reaches of stratified water persist behind these weirs until the flow exceeds a critical value necessary to mix the water column. Most irrigation deliveries exceed this threshold flow. However, when the discharge is less than the threshold for mixing, cold water inflows will move along the bottom of the weir pools where they have the potential to reinforce the thermal stratification. In the case of underflow weirs such as are used on the Murrumbidgee (e.g. Maude Weir), these flows may pass through the entire weir pool without significant warming because the surface layer and thermocline of the pool insulate the flow from the surface heat fluxes.

During most of the irrigation season is reasonable to assume the river is well-mixed. Under these conditions the temperature change associated with a given net heat flux decreases linearly with increasing average depth of the river. There is no direct dependence between temperature change and the surface area because the various surface heat fluxes are assumed to act uniformly over the entire surface of the river.

Data collected by CSIRO at Maude Weir (Murrumbidgee River) and Chaffey Reservoir showed maximum daily mean surface layer temperatures of 28 and 26 °C, respectively. It is not possible to sustain temperatures warmer than this and in fact typical temperatures are likely to be no warmer than 24-25 °C due to strong feedback in heat transfer. As the surface temperature rises above this equilibrium level, the rate of heat loss to the atmosphere due to evaporation and radiation increases rapidly enough to prevent any further long term increase in temperature. For example, an increase in water temperature from 25 to 28 °C will increase heat losses by approximately 70 W m^{-2} for an air temperature of 24 °C, relative humidity of 46% and wind speed of 2.5 m s^{-1}.

The average net heat flux at Chaffey Reservoir during the principal heating period from Sep-Dec was 48 W m^{-2}. This heat flux is sufficient to warm a 1 m-deep water column about 1 °C per day. Extrapolating this observation suggests that a 3 m-deep river with an initial temperature of 10 °C will have to travel some 6 weeks before it satisfies the threshold temperature of 23 °C desirable for several native Australian fishes given by Lugg (1999). Clearly, increasing discharge temperature at the dam has the potential to dramatically reduce the length of river impacted by cold water pollution.

Finally, it is important to recognise that it is not possible to mimic the diel temperature variations of a ‘natural’ stream if the flow rate is not also mimicked. The diel temperature variation decreases with increasing discharge due to the increase in thermal mass of the river. Typically, irrigation flows released during the summer greatly exceed the ‘natural’ flow for a river that would otherwise have occurred. While it may be possible to modify the mean temperature of the release using the mitigation techniques discussed in this report, it is unlikely that the natural temperature range will also be restored.

6 Thermal pollution remediation strategies

Stanford et al. (1996) discuss the ecological repercussions of river regulation and review remediation strategies for regulated rivers. They suggest a remediation protocol geared to allowing natural – as opposed to engineered (e.g. fish stocking, artificial in-stream structures) – processes to improve the riverine environment. They advocate restructuring dam operations such that flow and temperature regimes improve communication between river and floodplain and more closely follow the ‘natural’ water temperature patterns. Another general discussion of managing the water quality of reservoir releases is given by Cassidy (1986) who also discusses politically-driven operational constraints arising from highly variable discharges in the Rogue River Basin of Oregon, USA. Price and Meyer (1992) provide a good general overview and technical discussions of water quality management techniques used in a variety of US Army Corps of Engineer reservoirs.

Basically, there are two broad strategies to deal with thermal pollution downstream of dams: either exploit the stratification in the reservoir or destroy it. The first strategy relies on a phenomenon called ‘selective withdrawal’ which allows water to be withdrawn from particular regions within a density-stratified (either salt or temperature) water body and can be employed to combat both warm and cold water pollution. The latter strategy is typically implemented as some form of artificial destratification, either by the injection of compressed air at the bottom of the water column or by the operation of mechanical mixers and is useful only to combat cold water pollution. In this section, the underlying physical principles of these two strategies are described. The discussion of specific techniques are described later.

6.1 Physics of selective withdrawal

When water is withdrawn from a density-stratified water column, and assuming the volume of water withdrawn is small relative to the reservoir volume, the density gradient serves to constrain the region from which the released water emanates. As discharge increases, the velocity of the water within the reservoir as it approaches the outlet increases as well which in turn increases the thickness of the withdrawal layer. Fischer et al. (1979) provide a useful introduction to the applicable scaling laws. For most regulated releases, the expected withdrawal layer thickness can be expected to vary from 3 to 15 m as stratification varies from strong (1.2 °C / m) to weak (0.07°C / m).

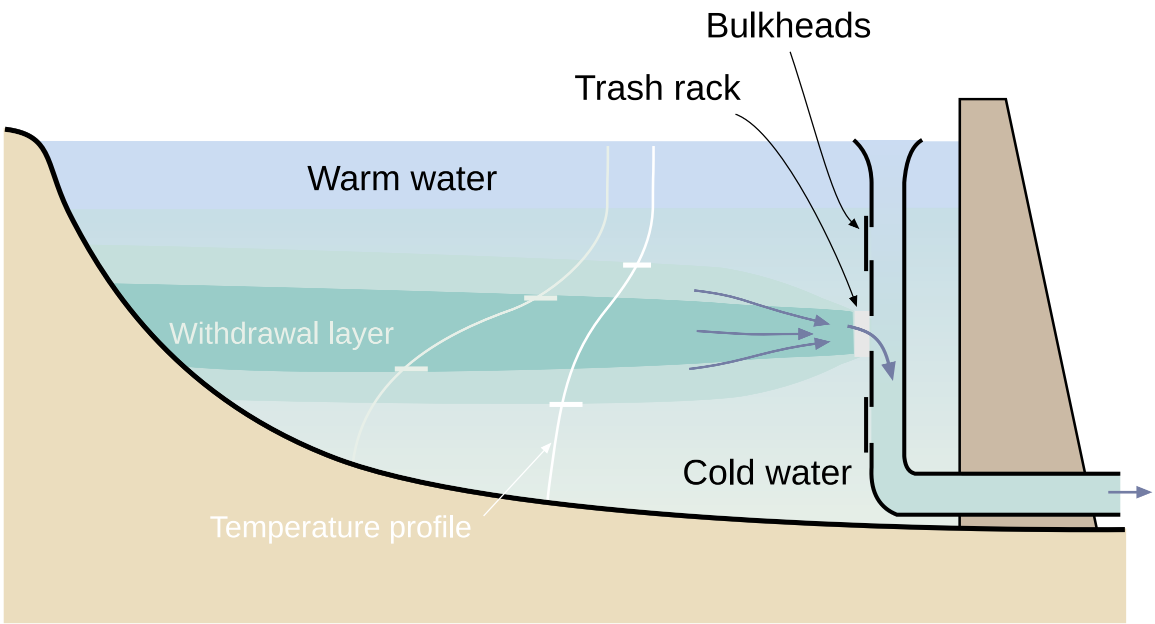

Figure 1 Selective withdrawal removes water from strata within the water column. It is usually done by replacing one or more bulkheads in a multi-level outlet structure with trash racks to screen out large debris while allowing water to pass through the dam. The thickness of the withdrawal layer depends on the strength of the stratification and the discharge rate.

To exercise control over the discharge temperature, the level of the outlet may be varied so that water from the withdrawal region has the desired characteristics. Usually this is achieved by constructing a multi-level outlet structure (MLO) with several openings located at fixed levels above the bottom. Water is withdrawn from one or more withdrawal ports by replacing bulkheads with trash racks.

6.2 Destratification

Reservoirs may be artificially destratified in order to reduce the temperature difference between the bottom and the surface. This is accomplished by inducing a large scale circulation within the reservoir through the introduction of bubble plumes or the use of mixers. In either case, cold water is pumped from the lower portion of the water column up to the surface as a cone-shaped jet or plume that entrains ambient fluid from throughout the water column on its way to the water surface. At the surface the jet/plume has a temperature between the top and bottom water column temperatures and after spreading out radially over a short distance (~5-7 m), it plunges to a depth where its density matches that of the reservoir and then intrudes into the body of the reservoir at this depth.

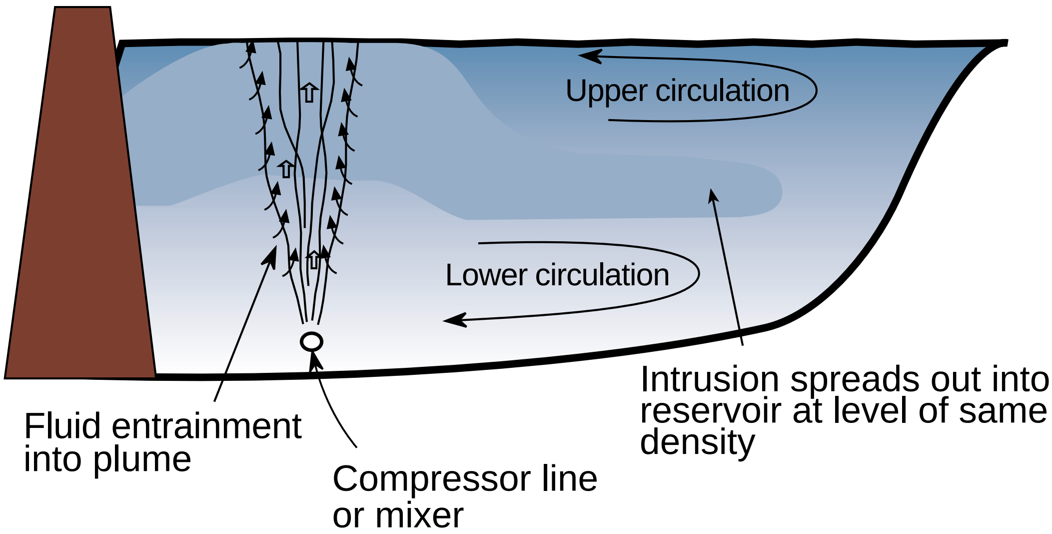

Figure 2 Typical circulation pattern set up by artificial destratification.

The resultant circulation typically consists of two gyres (although more are possible) with flow away from the plume at the intrusion depth and return flows both above and below the level of the intrusion (Figure 2). The net effect of this circulation is to produce a ‘falling’ reservoir where the profiles of temperature, dissolved oxygen, etc. can be imagined as descending at a rate determined by the requirement to conserve the mass flux arising from the vertical flow of water within the jet/plume. As the number of jets/plumes increases so too does the circulation, which accelerates the rate of destratification.

Limitations on the effectiveness of artificial destratification are largely dictated by the local climate and the size of the storage to be destratified. Larger reservoirs require larger destratification systems and therefore higher capital investment. Lorenzen and Fast (1977) proposed a rule of thumb of 150 L/s of compressed air per 100 ha of reservoir surface area. Design recommendations based on more detailed theoretical analysis of bubble plumes are also available (Schladow 1992). The larger a destratification system is, the faster it can achieve a desired amount of destratification. As the stratification weakens, artificial destratification typically becomes less energy efficient, i.e. the cost to reduce the top-to-bottom temperature difference by another 50% increases. The loss in efficiency as destratification proceeds is unlikely to be important for cold discharge mitigation where raising the temperature of the hypolimion to within 2-3 °C of the surface layer temperature may possibly be sufficient. Once the desired hypolimnetic temperature has been reached, the system can be shut down bearing in mind that other water quality issues such as increased rates of oxygen depletion will likely result.

7 Remediation measures

7.1 Destratification

7.1.1 Theory

Destratification of the entire water column will raise temperatures of the entire hypolimnion thereby increasing the temperature of bottom releases. Destratification works by increasing the circulation within the reservoir in such a way that relatively warm, oxic water from near the surface is transported downwards to the bottom. The rate at which this transport occurs increases nearly linearly with increases in the airflow rate or mixer discharge assuming proper design of the destratification system. Destratification generally will increase dissolved oxygen concentrations in the hypolimnion providing greater potential habitat for fish and zooplankton. The increased temperature also increases the rate of hypolimnetic oxygen demand. Care must be taken to avoid undesired side-effects such as resuspension of sediment.

If raising release temperatures is the sole objective of destratification, then operation of the destratifier need take place only from spring through early summer. As soon as the minimum reservoir temperature exceeds the desired threshold the system can be turned off. Once destratified, there is no longer any possibility of releasing colder water until the following winter. This strategy assumes there is no external source of unseasonably cold water that would subsequently enter the reservoir during summer or autumn. An important consequence of this approach is that upon cessation of operation, anoxic conditions would rapidly be re-established in the hypolimnion along with the production of toxic hydrogen sulphide which may in itself require mitigation prior to release downstream.

7.1.2 Experience

Abundant experience with destratification (e.g. Chaffey Dam) confirms that an appropriately sized system can effectively raise the temperature of a reservoir to close to the mean average daily air temperature. This method can also reduce significantly the internal nutrient load from the sediments if catchment geochemistry is appropriate, which it commonly is.

Local destratification adjacent to outlet structures has been used successfully by the Tennessee Valley Authority (TVA) to reduce condenser cooling water temperatures at Belews Creek Fossil Plant (Mark Mobley, pers. comm.). In this application a bubble plume was used to raise cooler hypolimnetic water to directly in front of the intake for the power plant’s cooling system. The plume is sized so as not to destratify the reservoir. Note that it is strictly a misnomer to refer to this as destratification as it is simply air injected to lift water into the outlet with little or no impact on overall stratification.

7.1.3 Cost

North Pine Dam (Lake Samsonvale) is a large reservoir that supplies water to the city of Brisbane. It is a large reservoir (~350,000 ML) and has a 'state-of-the-art' bubble plume destratification system. The system cost $400,000 to build and approximately $100,000 p.a. to operate (G. Grant, pers. comm.). The destratifier was installed to help control cyanobacterial growth and although it has not eliminated a discrete, persistent, relatively shallow surface mixing layer, it has reduced the internal nutrient load with consequent reductions in algal biomass.

7.1.4 Projected cost for large New South Wales irrigation storages

We can extrapolate from the North Pine Dam experience to estimate the cost to install a system for the larger dams in New South Wales that have been identified as most urgently requiring attention. Four of these dams hold in excess of 1,000 GL and because the size of these systems (in terms of airflow rate) scales linearly with volume, a capital cost of $1.5m serves as a low estimate. Three months continuous operation is conservative, 6 weeks is probably adequate possibly in 2-3 week bursts during which the temperature is ratcheted up. The operating cost will depend on the compressor size and the depth of the reservoir to be destratified. A simple scaling of the North Pine Dam experience, i.e. 3 times the air flow rate for 1/4 – 1/3 the period of operation (assuming no need to operate the system for other water quality objectives) suggests an annual operating cost of at least $75,000 - $100,000 per annum.

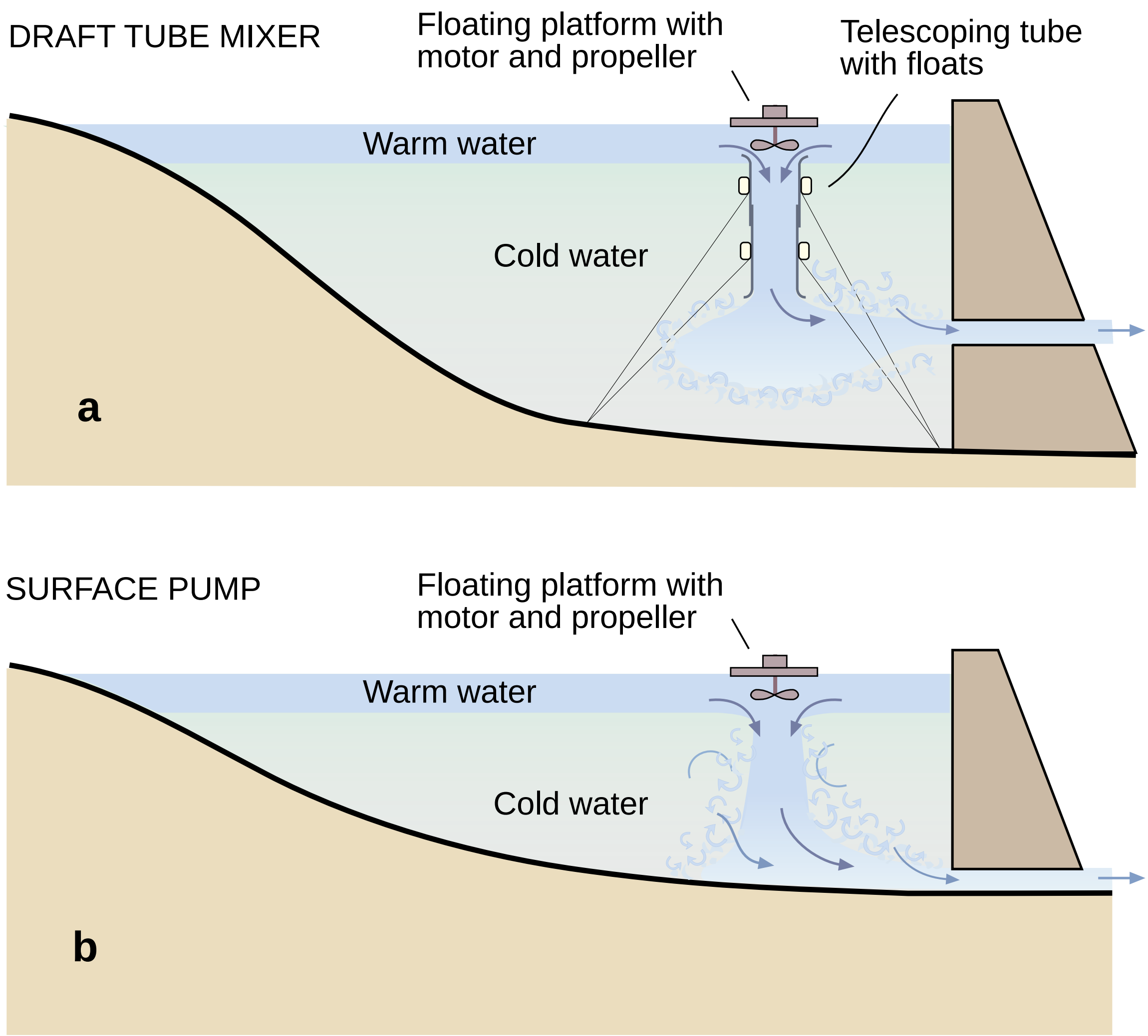

Figure 3 Surface pumps send surface layer water downwards into the withdrawal layer adjacent to the outlet. a) The use of a draft tube decreases entrainment of reservoir water and can increase the energy efficiency of the system. b) An unconfined jet issuing from the surface pump is the simplest type of system to construct.

7.2 Surface pumps

7.2.1 Theory

Surface pumps are sometimes used to 'locally destratify' reservoirs in the vicinity of the outlet works (McLaughlin and Givens 1978; Garton 1981; Robinson 1981). In fact, 'local destratification' is something of a misnomer as these systems are not intended to alter the stratification on a basin-wide scale. Instead, the large diameter (1.5-5 m) impellers are used to improve release water quality by pumping warm surface layer water through the thermocline into the withdrawal region adjacent to the outlet which may be located anywhere between the surface and the bottom of the water column (Figure 3).

Typically, the impellers are powered electrically. Frequency control devices on the power supply can be used to alter the rotational speed, and thereby the flow, of the pumps (Mobley et al. 1995). As the pump speed increases, the velocity of the jet increases and it penetrates further down through the stratified water column. Power consumption also increases with increasing pump speed. In practice, a pump should be operated to penetrate to the invert of the outlet, but not much further Figure 3a.

McLaughlin & Givens (1978) present a useful discussion of surface pump theory and some basic design considerations. The release water quality depends on the release rate, the pump flow rate, and the amount of water entrained into the jet. Release water quality is often parametrised in terms of a dilution factor which is simply the proportion of surface layer water in the release. The horizontal location of the pump relative to the outlet is also important.

As an unconfined jet propagates away from the impeller it entrains water from the reservoir (Figure 3b) and the mean velocity of the jet decreases in order to conserve momentum. As the velocity decreases, the ability of the jet to further penetrate the thermocline decreases. Draft tubes can be used to prevent unwanted entrainment (Figure 3a) and increase the energy efficiency of the system by allowing lower pump speeds to deliver a given flow to a specific depth. However, draft tubes increase the complexity of the construction and installation and care must be taken in designing the draft tube to allow for drag on the tube and to accommodate changes in water level. As the reservoir is drawn down, the distance to a fixed outlet changes and it may be necessary to alter the length of the draft tube to cope with the change.

The major design considerations are: water surface fluctuations; loadings due to wave action; and required pump plume velocities (Mobley et al. 1995). Some concern has been expressed that, on safety grounds, impellers may not be suitable for storages with public access (B. Hindmarsh, pers. comm.). Care must be taken to prevent the passage of debris through the impeller blades and to limit access to reduce the threat of vandalism. Because surface pumps are typically mounted to the outlet structure or dam wall, public access is usually avoided by existing security measures.

7.2.2 Experience

The most relevant field experience with surface pump systems is reported by Mobley *et al.* (1995). They present construction details (pumps, rafts, wall mounting) and operational results for the surface pumps used at Douglass Dam on the French Broad River in Tennessee. The dam has a normal turbine flow of 450 m^3s^{-1} and the system was designed so that 1/3 of the total flow should originate from the surface layer. The system consisted of nine 4.6 m diameter stainless steel impellers each driven by a 30 kW motor with variable frequency controller to allow variable pump speeds. Each impeller had a design pump rate of 15 m^3s^{-1}.The system had to allow for a 19-m range of vertical movement to accommodate changes in water level.

The system raised dissolved oxygen in the release water by 1.5-2 mg L^{-1}. This water would otherwise have been anoxic. It appears that nearly all of the pumped surface layer water passed through the turbines (1/3 of flow with 6 mg-O_2 L^{-1}, 2/3 of flow with 0 mg-O_2 L^{-1}). The pumps worked more effectively when located side by side so that the plumes combined and entrainment was reduced. The system has performed satisfactorily with no significant failures after the initial compliance testing phase.

Other early field tests of prototype impellers have confirmed further the utility of surface pumps to improve release water quality (Garton 1981; Robinson 1981). These authors reported on tests of impellers of various diameters for which Q_p / Q_r varied from 0.29 – 4.0 (Q_p = pump flow rate, Q_r = release flow rate). They observed that up to 80-85% of the release could originate from within the surface layer. They also observed that resuspension of sediments could decrease the improvement in release water quality when the dam outlet is located near the bottom and the jet impinges upon the sediments (Robinson 1981).

Draft tube surface pumps are currently undergoing serious study in Australia as a possible means of algal control through reduction of surface layer residence time. Brian Kirke (Griffith University) and I have made preliminary observations of the impact of a draft tube low velocity impeller deployed at Little Nerang reservoir (volume ~ 10,000 ML). This mixer consumed 3 kW and generated a flow of approximately 4 m^3s^{-1} which was delivered to a depth of about 11 m through a draft tube. Four weeks of operation was sufficient to raise the temperature by 3 °C at depths above 16.5 m throughout the storage. This prototype impeller was the precursor to the surface pumps subsequently installed by SA Water and the Cooperative Research Centre for Water Quality and Treatment (CRCWQT) in Happy Valley and Myponga reservoirs in South Australia. The performance of the South Australian mixers is currently the subject of a CRCWQT research project.

7.2.3 Cost

Mobley et al. reported that the total capital cost for the Douglass Dam system was $2.5m with mechanical equipment and rafts costing $1.5. Operating costs were estimated at $5,000 per month at local commercial rates. The continuous power requirement of the TVA system was 270 kW.

The improved design used in the Myponga reservoir mixer units draws 3 kW to send a flow of 6.8 $m^3 s^{-1}$ to a depth of 15 m. Each mixer cost $125,000 which includes a maintenance contract component. The manufacturer, WEARS, lists the price of the mixers at $60,000 but required design modifications suggest that a higher cost of at least $100,000 should be budgeted for. To achieve a flow rate of 135 m^3s^{-1} (i.e. comparable to the TVA flow rate) would require 20 of the 3 kW units so the total power consumption would be about 60 kW or roughly 1/4 that of the TVA system.

7.3 Selective withdrawal using multi-level outlet (MLO) structures

Selective withdrawal is the single most common technique employed to control the temperature of downstream releases and there is a wealth of experience to draw upon. If the presentations at the recent North American Lake Management Society (NALMS) conference (Reno, Dec 1999) are indicative of current practices in general, retrofitting of dams with MLOs is the most common technique for the mitigation of thermal pollution below dams.

7.3.1 Theory

Multi-level outlet structures exploit the stratification within a reservoir by allowing water with desirable attributes to be withdrawn from relatively confined regions within the water column. Outlets may be used singly or in combination with one another to produce a release with better characteristics than would be available from a single outlet. When used to raise discharge temperature, selective withdrawal takes water from further up the water column which also may provide higher dissolved oxygen and possibly higher algal concentrations in the release.

As more outlets are provided, greater control over the withdrawal region results but at the cost of higher capital expenditure. On the other hand, if too few outlets are provided reservoir level fluctuations might interfere with selective withdrawal as fixed level outlets may not provide access to water of desired quality (Lee 1986; Department of Public Works and Services 1996a).

Lee (1986) presented a method that allows one to choose a selective withdrawal capacity that maximises the benefit to the downstream fishery. The method involves exploring the complete parameter space (e.g. inflow and outflow volumes, outlet levels, etc.) to find combinations that minimise the deviation of downstream temperatures from desired levels.

Computer-based optimisation techniques have been used to determine release strategies using MLOs that minimise the deviation of the release water temperature from the desired water temperature (Price and Meyer 1992). There are numerous reports regarding design (Lee 1986; Vovk and Horihan 1986; Hall 1986a, 1986b, 1986c; Johnson 1988; Howington 1990) and operating (Cassidy 1986; Lee 1986; Holland and Fontane 1990) considerations for MLO structures.

7.3.2 Experience

The performance of MLO structures is straightforward to predict and field results confirm theory in most cases. Occasionally basin morphometry must be considered, especially in reservoirs with sills and narrow reaches sufficiently close to the outlet that they modify the hydrodynamics of the flow. In practice, some MLO structures have been cumbersome to use, requiring 1 man-day or more to move bulkheads and trash racks in order to reset the outlet level.

7.3.3 Cost

The costs associated with retrofitting a dam with a multi-level outlet structure is typically quite high. Costs increase dramatically for deeper dams, due to both increased material costs and increased construction costs, especially if divers must be used. Estimated and actual costs for retrofitting several large dams are shown in Table 2.

Table 2 Estimated costs for retrofitting existing dams with multi-level outlet structures. The actual cost is shown in the case of Shasta Dam (USA). Data from Department of Public Works and Services (1996).

Dam	Volume (GL)	Estimated Cost (% of volume covered)
Blowering	1631	$10m (85%) - $15m (100%)
Burrendong	1190	$5m (55%) - $25m (100%)
Wyangala	1218	$5m (60%) - $10m (100%)
Keepit	426	$10m (95%)
Copeton	1361	$10m (80%) - $30m (100%)
Carcoar	36	$3m (85%) - $5m (100%)
Shasta Dam	5400	$USD 80m (actual)

7.4 Floating intakes (Trunnions)

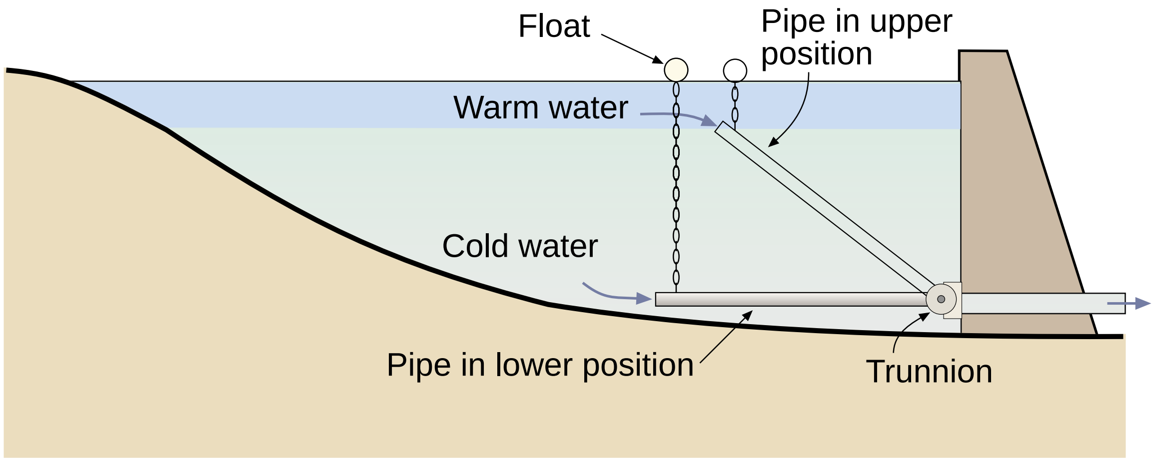

Figure 4 A trunnion intake structure.

7.4.1 Theory

The use of trunnions is another variation on the theme of selective withdrawal. In this case a pipe is hinged at the dam wall and the free end is suspended from the surface. The use of trunnions is limited to low discharge applications because of the difficulty and cost of constructing and operating large diameter submerged pipes (B. Hindmarsh, pers. comm.). They are therefore most likely not practical for irrigation releases.

Trunnions longer than 25-30 m are not likely to be feasible. An important consequence of this is that deep dams would still require multi-level outlet structures with a trunnion located on each outlet to guarantee access to the entire water column.

7.4.2 Experience

In Australia, a number of smaller dams with low discharge requirements are fitted with trunnion intake structures because they are relatively inexpensive and simple to construct. The Sydney Catchment Authority uses trunnions at its water supply reservoirs in the Blue Mountains. It appears that the variable level outlet capabilities have not been exploited. Instead, the intakes have been suspended at the same depth below the surface throughout the operation of the dams. This has provided the desired raw water quality so there was no need to vary the level of the outlets although this capability is easily available.

NSW Public Works Dept. has recently retrofitted Chifley Dam with the largest trunnion system ever deployed in Australia (D. Jamieson, pers. comm.). Two identical 700 mm diameter pipes have been attached to the bottom outlet with a total discharge capacity of 100 ML / day. Each pipe is 25 m long, designed for a normal operating head of 19 m and should provide access to a water column depth range of 15-20 m. Installation required expensive underwater works including excavation of silt and debris, and attachment of a suitable base to allow connection of the trunnion to the existing outlet works.

7.4.3 Cost

The trunnion systems used by the SCA were built in the 1930s and no information was readily available regarding their cost. The tendered price for the trunnion retrofit at Chifley Dam was $1.63 m – significantly higher than the design estimate of $900,000.

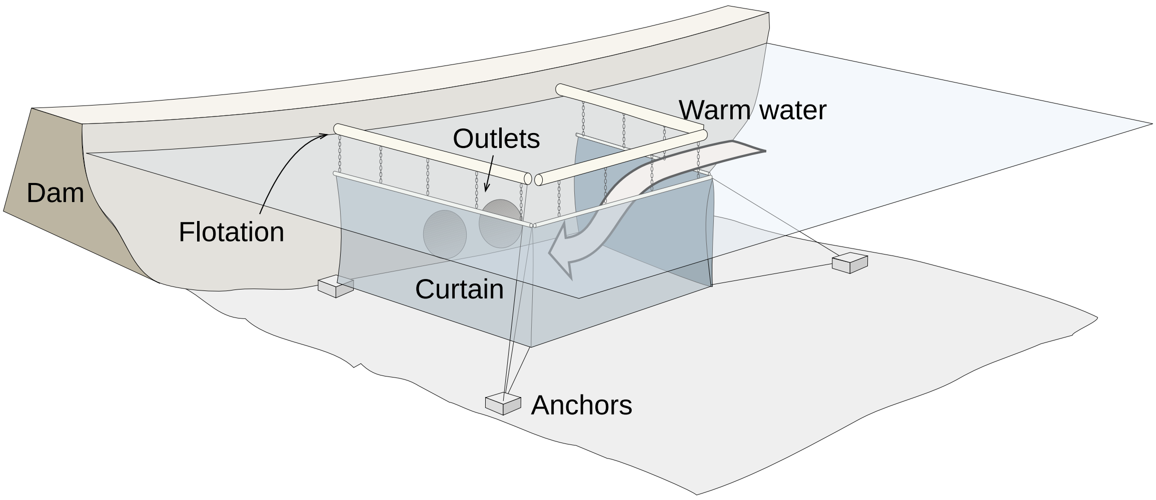

Figure 5 A submerged curtain forces the release to originate from within the warmer surface layer of a reservoir.

7.5 Submerged weirs, suspended curtains

7.5.1 Theory

Curtains made of a robust polymer (Hypalon) are suspended from the surface using cables and floats. Curtains may be deployed at any depth and provide a barrier to the passage of water. Suspended from the surface they force cooler water to pass underneath and increase the residence time of the surface layer upstream of the curtains. Raised above the bottom, they allow passage only of warmer water from above the top of the curtain.

7.5.2 Experience

During the early 1980's the California Dept of Water Resources experimented with a suspended curtain in Lewiston Lake in order to raise the temperature of the surface layer which supplied water to a fish hatchery (Boles 1985). The function of the curtain was to provide a selective withdrawal capability for a tunnel used to transport water to another reservoir. The aim was to decrease the amount of water diverted from the surface layer into the tunnel so that the fish hatchery could enjoy warmer water. Use of the curtain during 1983-1984 raised the surface layer temperature by 2-3 °C before the vinyl curtain failed in 1984. Bohac (1989) reports on TVA's use of a submerged curtain to prevent cold hypolimnetic water being released downstream.

Vermeyen (1997) provides a very detailed report on the design, construction and operational performance of curtains suspended downwards from the surfaces of Lewiston and Whiskeytown Reservoirs to reduce heat gain of the flow through these storages before finally being released into the Sacramento River.

Stuart Angerer (US Bureau of Reclamation, pers. comm.) has advised me recently that the curtains installed at Whiskeytown Reservoir are starting to wear after 8-9 years, which is their expected life. Of particular concern are stresses such as sediment accumulation on the material when the water level drops which causes the curtain to sag with the slack getting covered up. There is also concern about their robustness in the event of flood events, i.e. the stress due to drag from the movement of water may cause accelerated wear or failure of the curtain fabric. Permanent deployments wear better than do curtains that are annually removed and redeployed.

In Japan, curtains have been used to prevent the spread of cyanobacterial contamination of the surface layer of a reservoir (Asaeda, pers. comm.). The curtains were deployed in such a way as to form a barrier between the water surface and a depth of about 5 m in order to confine warm nutrient-rich inflows to the upstream endof the reservoir. All downstream flows had to pass beneath the curtain. The deployment proved effective in this regard. This experiment was not concerned with the control of discharge temperature.

7.5.3 Cost

Vermeyen (1997) provides extensive costing data and describes specific design improvements made as a result of component failures. Dimensions and capital costs for construction are given in Table 3. Operating and maintenance costs for all four curtains totaled $160,000 during 1993-1995 and a further $500,000 is estimated to be required by 1999. O&M costs were nil for Lewiston reservoir curtains which did not experience significant loading and did not need to be recovered and redeployed each year. The anticpated $500,000 charge is for recoating of steel components and presumably all four curtains require this maintenance.

Table 3 Curtain capital costs

Site	width (m)	height (m)	cost USD	cost / m^2
Lewiston	249	10.5	$650,000	$249
Lewiston fish hatchery	90	13.3	$150,000	$125
Carr Powerplant tailrace	180	12	$500,000	$231
Spring Creek Intake	720	30	$1,800,000	$83

7.6 Stilling basins

7.6.1 Theory

A stilling basin is simply a large shallow pond through which the reservoir release passes. It delays the downstream movement of the release and therefore allows more time for the release to approach thermal equilibrium with the atmosphere. As the volume of the basin increases so does its residence time (the time for the water to travel through the basin). As the surface area of the basin increases, a greater amount of heat is transferred between the water and the atmosphere since the rate of heat loss (W m^{-2}) is the same regardless of basin size. Both longer residence time and greater heat transfer accelerate the approach to thermal equilibrium. To mitigate cold water pollution, a basin should have as large a volume and surface area as possible. Unfortunately, a greater surface area also increases evaporative losses and possibly leakage to groundwater so the optimum design involves a trade-off between land and construction costs, water loss and more rapid temperature adjustment.

To raise the discharge temperature by 1 °C / d suggests a simple design criterion of 1 km^2 surface area per 1000 ML / d of discharge. When considered in the context of a maximum release from Burrendong Dam, a 8 km^2 stilling basin would provide just a 1°C boost in temperature before the release continued on its way downstream.

7.6.2 Experience

Cooling ponds used by industry, e.g. in electricity production, are an example of a stilling basin. Industrial applications do not treat volumes of water comparable to irrigation releases and experience with them is not directly applicable to cold water pollution mitigation. No reference was found regarding first-hand experience with the use of stilling basins to mitigate cold water pollution, however Public Works and Water Supply (1996a) does mention them as a possible option for use in conjunction with hydroelectric projects. Their feasibility depends on local site conditions.

7.6.3 Cost

The simple design argument presented above suggests that stilling basins are unlikely to be feasible because of high construction costs and possible lack of suitable space.

7.7 Modified guide or rule curves

7.7.1 Theory

The operation of reservoirs may be adapted to alter the residence time of the storages in order to improve discharge water quality. Reservoir operators enjoy greater flexibility in the implementation of this method for reservoirs operated in series such that both upstream and downstream releases may be manipulated. This approach is discussed by Price and Meyer (1992). In general, it is desirable to use computer simulations to predict the impact of modifications to operating practices.

7.7.2 Experience

According to Price and Meyer (1992), reports on field experience with this method are limited to the initial filling of reservoirs although it is a recognised method for ongoing reservoir operations. Some laboratory studies have demonstrated its feasibility (Price and Meyer 1992).

7.7.3 Cost

Because no capital costs are involved, the cost of modified operating procedures will mainly reflect costs associated with changed timing of hydropower and irrigation releases.

8 Summary

The options that are most technically feasible to warm irrigation releases below large dams are the use of surface pumps, destratification, retrofitting with multi-level outlet structures and submerged curtains. For irrigation flows stilling basins would likely have to be impossibly large to provide a satisfactory increase in temperature whereas trunnions are not capable of transporting the flows required.

9 Acknowledgements

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10 Appendix A – Case Study of Burrendong Dam

10.1 Introduction – the challenge

In this section, I present a comparison of designs and rough costings for the installation and operation of a surface pump system and a submerged curtain to mitigate cold water pollution below Burrendong Dam on the Macquarie River. These two strategies have been chosen because I believe they are the only feasible alternatives to retrofitting a dam with a multi-level outlet structure when large discharges are required. The aim here is to improve the reader's insight into the trade-offs between various design and operational constraints as well as providing a common basis for the comparison of two very different mitigation strategies.

Burrendong Dam has been chosen because it is currently the site of research conducted by NSW Fisheries into the effects of cold water pollution on Australian native fish and so would serve as a useful location to test a prototype system because of the availability of historical data as a basis for comparison. Being a large reservoir with significant irrigation releases, the site also would provide a rigorous test of the feasibility and effectiveness of the two cold water pollution mitigation strategies.

Figure 6 shows clearly the impact of the cold releases from Burrendong Dam – a 10-11 °C decrease in temperature between the inflow and the discharge. Under natural conditions, the river would likely be suitable for most native fish for some 400 km downstream of Long Point. Cold water pollution has made the 300+ km downstream of the dam unsuitable. Any increase in the discharge temperature would increase the amount of suitable habitat. As the release temperature increases, the upstream boundary of suitable spawning habitat (currently located near Warren) moves upstream as well.

One may imagine the improvement provided by a specified increase in discharge temperature using Figure 6 and shifting the observed temperature line downstream of Burrendong Dam to the left to match the discharge temperature below the dam and then extrapolating the plot in the downstream direction. This is illustrated in the figure for discharge temperature increases of +5 and +8 °C. Because of the relatively slower rate of temperature increase for temperatures above 20°C, the +8 °C scenario yields nearly 200 km more river wherein the temperature exceeds 23°C, which provides more suitable spawning temperatures for native fish. The challenge here is to increase discharge temperature as much as possible while minimising cost.

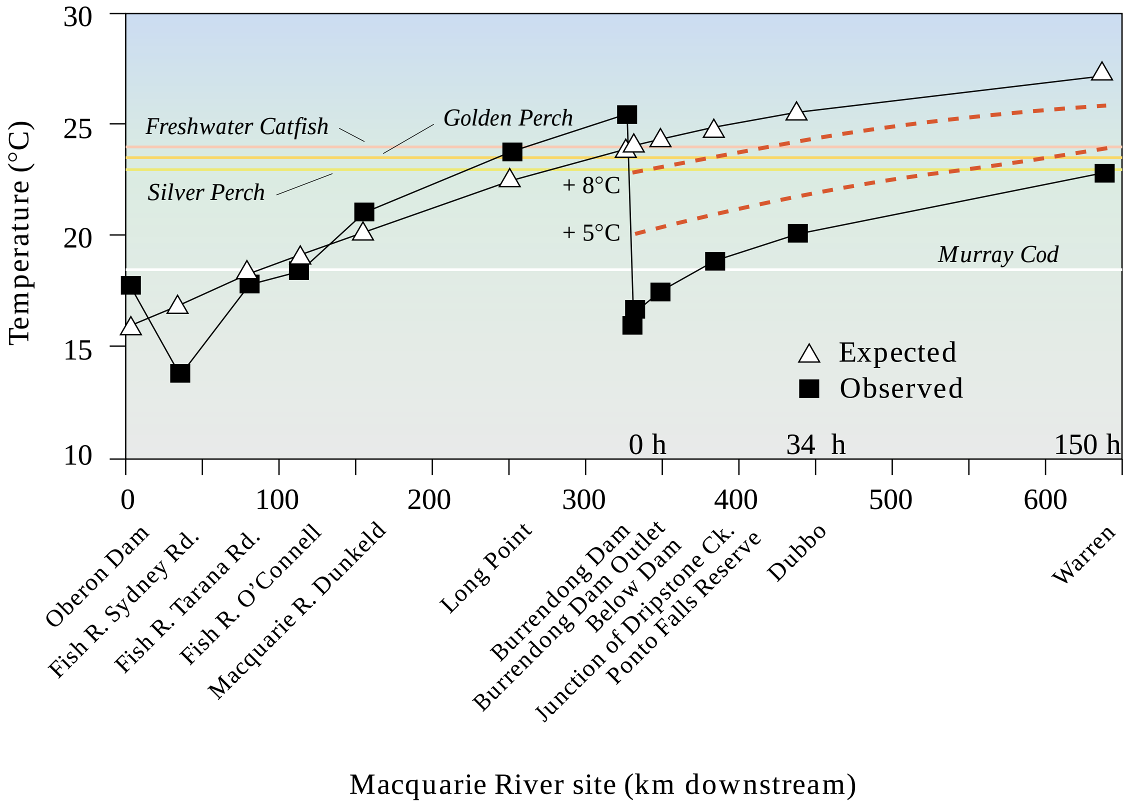

Figure 6 Observed and expected river temperatures above and below Burrendong Dam. Also shown are the desirable spring-summer temperature requirements for successful spawning of several native Australian fish species (horizontal lines) and the projected river temperatures for increases in the discharge temperature of 5 and 8 °C (heavy dashed lines). Travel time under high flow conditions is 34 h from the dam to Dubbo and 150 h to Warren. Temperature data from Harris (1997).

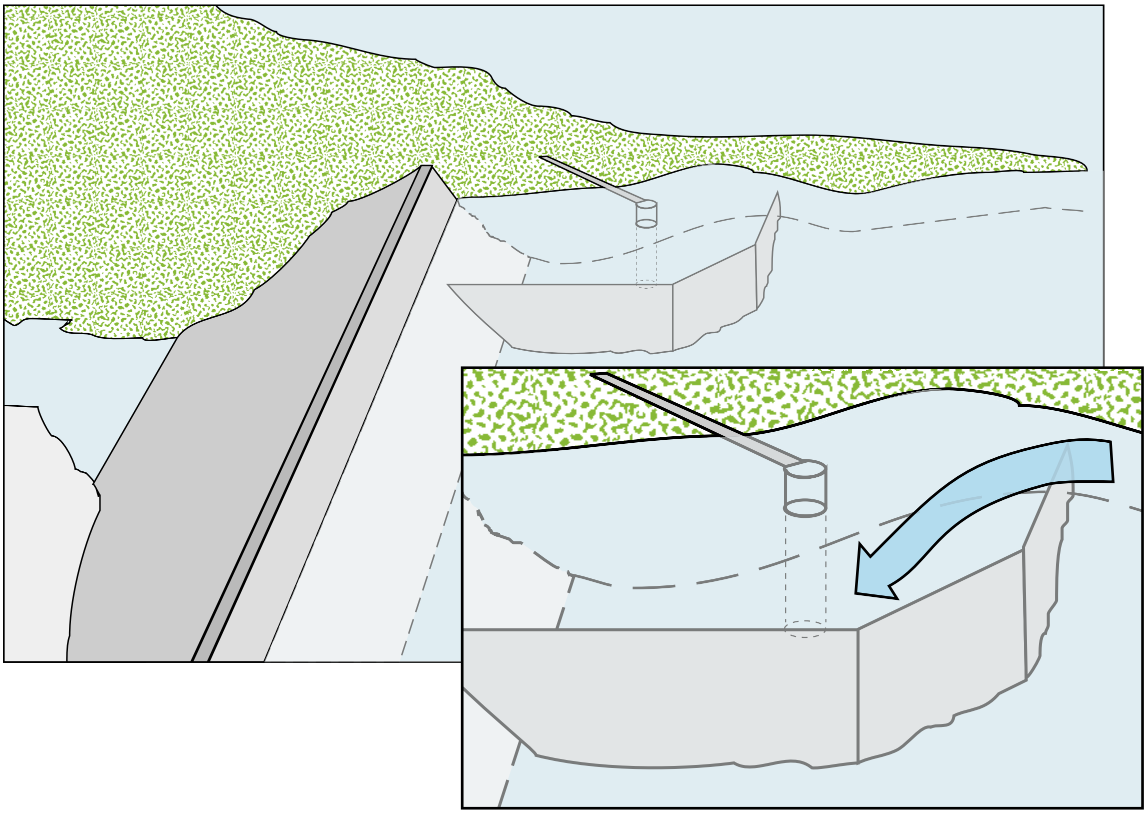

Figure 7 Conceptual diagram of Burrendong dam, outlet tower and the proposed submerged curtain.

10.2 Site description

Burrendong Dam is located on the Macquarie River about 30 km southeast of Wellington, New South Wales. The dam has a storage capacity of 1678 GL, surface area of 89 square km and a maximum depth of 50 m. When full, the surface level is 344.73 m AHD. All controlled releases from the dam pass through a single round outlet, 3.2 m in diameter, centred about an elevation of 312.58 m AHD (i.e. invert at 310.98 m AHD). The outlet is situated at the bottom of a circular tower roughly 14 m in diameter and located 50 m from shore (Figure 7). The reservoir's spillway is located over 1 km away on the opposite side of the peninsula from the outlet so that spillway flows are unlikely to induce significant velocities in the vicinity of the outlet.

10.3 Design considerations - reservoir operation

The theoretical maximum controlled release from the dam is 7900 ML/d of which a maximum of 3400 ML/d passes through a hydroelectric plant. Examination of the release pattern from 1993-1999 (Figure 8) shows a maximum release of 6600 ML/d (= 76 m^3/s) and a mean discharge of 3400 ML/d (= 40 m^3/s). The water surface level typically decreases by about 5 m during the irrigation season but has fallen by up to 17 m during the 1997-1998 drought.

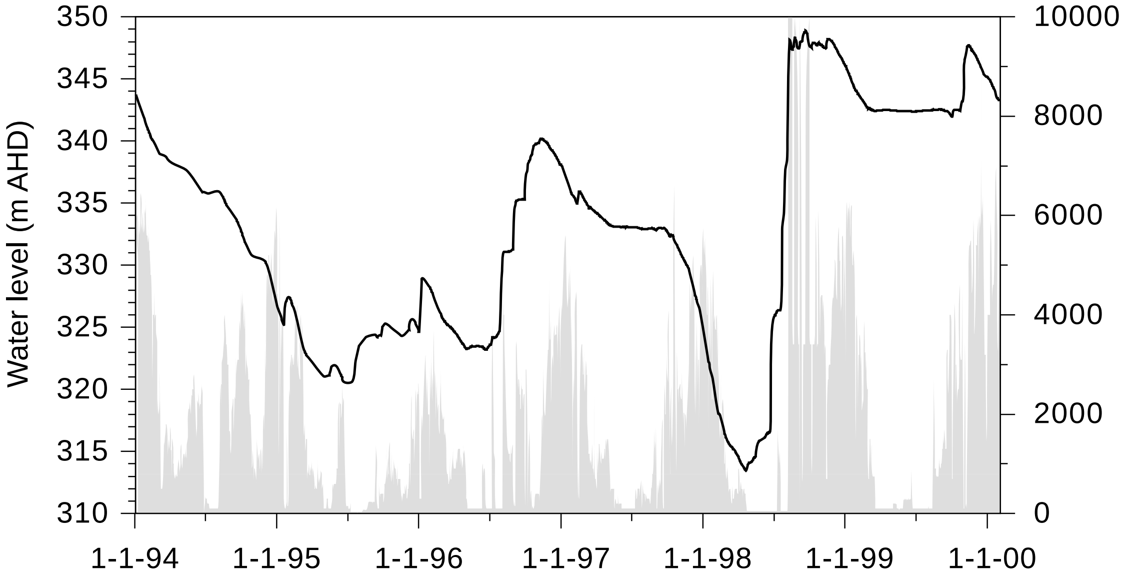

Figure 8 Water surface elevation (line) and discharge (grey region) at Burrendong Dam.

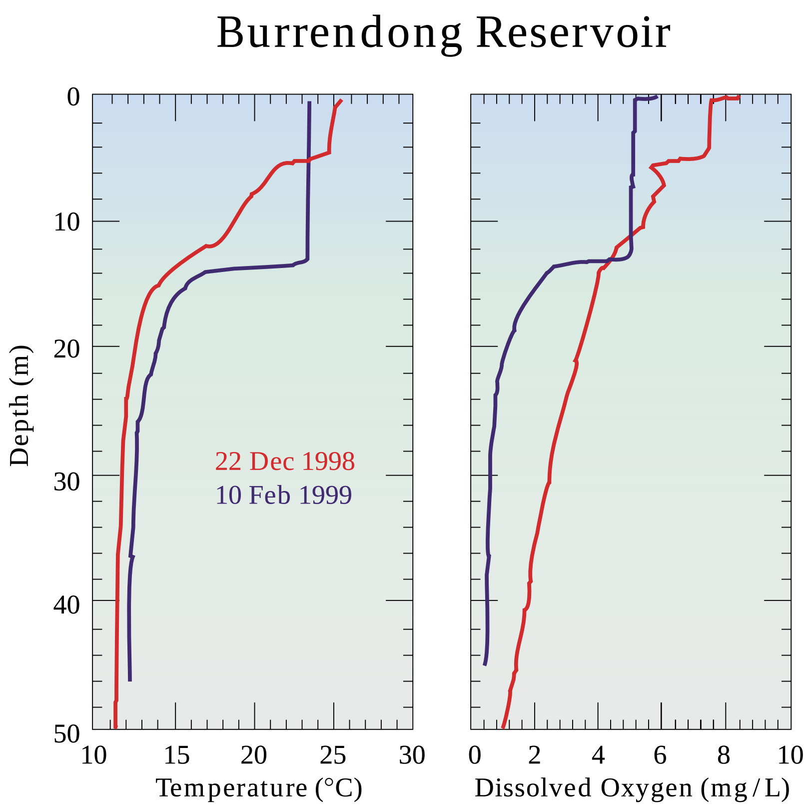

Figure 9 Temperature and dissolved oxygen profiles during typical summer conditions at Burrendong Reservoir.

Under typical summer conditions, the stratification in the reservoir consists of a 2-10 m thick thermocline that separates a 4-12 m well-mixed surface layer from the cold hypolimnion (Figure 9). The temperature of the surface layer is approximately 24 °C and that of the hypolimnion is about 12 °C. Because the outlet is located near the bottom of the hypolimnion, water withdrawn from the dam is typically very cold and anoxic. Temperatures seldom exceed 15 °C at a depth of 15 m.

The large discharges limit the available options to one of the following: surface pump; submerged curtain; or selective withdrawal. Destratification of such a large reservoir is not economically feasible. Similarly, trunnions big enough (ca. 3.2 m in diameter) to handle the large releases are likely to be very expensive to construct and the outlet works would have to be modified at considerable expense because a single trunnion would not provide adequate coverage of the reservoir's depth.

10.4 The options

10.4.1 Selective withdrawal

To provide the maximum temperature increase to the discharge, the retrofitted multi-level outlet would ideally constrain releases to the top 6 m of the water column (see the 22 Dec 1998 temperature profile in Figure 9). This could be accomplished with a design similar to that at Chaffey Dam, i.e. individual bulkheads and trash racks are 2 m high and about 3 m wide. Two trash racks would be inserted so that water would be released from between 2-6 m. Because the water level usually drops by about 1 m per month it would be necessary to relocate the trash racks every 6-8 weeks.

Selective withdrawal could also be used to release water from just below the surface layer, say from 6-10 m, when the stratification is similar to that shown for 22 Dec 1998. In this case the discharge temperature would be close to 20 °C compared to about 23 °C expected for a 2-6 m release, and undesired contaminants in the surface layer such as blue-green algae may be avoided in the discharge water.

The cost of retrofitting Burrendong Dam with a multi-level outlet structure has been estimated at $5m for 55% of the storage volume and $25m for 100% coverage (Department of Public Works and Services 1996a). The low end of the cost range would provide coverage only to a level of roughly 335 m. Because the water level is below this elevation about half the time (and often for years at a time, Figure 8), effective cold water pollution mitigation would require modifications at the expensive end of the range, i.e. close to $25m.

10.5 Surface pumps

10.5.1 Unconfined surface pump

The simplest surface pump deployment is one without a draft tube so that the pump produces and unconfined jet that propagates downwards. It is essential that the jet possesses sufficient momentum to reach the outlet at the bottom. The proposed design is for two 4.9 m diameter impellers (Lightnin Mixers A6000) mounted to the existing outlet structure and with the blades located 5 m below the surface. Vertical movement of the pontoons supporting the mixers will require a rail (like an I-beam) mounted to the outlet structure. Rollers on the pontoons fit into the rail allowing the pontoons to follow changes in water level while remaining attached to the outlet structure.

The design flow through each impeller is 15 $m^3 s^{-1}$. In addition, the jets must be able to propagate up to 28 m (when the reservoir is full) against a maximum density difference of 2.4 kg m^{-3}. To generate such a flow each pump would require a 30 kW electric motor. Both TVA experience and theory suggest that the jets should reach the outlet even under the strongest anticipated stratification.

For a full reservoir with a jet propagating 28 m, entrainment of ambient water increases the volume flux of each jet from 15 to 26-30 $m^3 s^{-1}$. The mean required discharge of 40 $m^3 s^{-1}$ would therefore require at least two pumps or an acceptance of a lower temperature increase for the discharge as any flow not provided by the pump will originate from within the cold hypolimnion. For a water level 10 m lower (a more typical level, see Figure 8), entrainment may increase the volume flux up to 24 $m^3 s^{-1}$ and again a minimum of two pumps would be required. It is very difficult to provide more exact estimates of the entrainment flux into the jet because the characteristics of large diameter buoyant jets close to the jet origin, i.e. the impeller, have not been studied in detail.

To satisfy the maximum discharge under any conditions would require either five pumps operating at 15 $m^3 s^{-1}$ or the use of three pumps with at least two operating at increased rotational speed to increase the volume flux through the impeller of 25-30 $m^3 s^{-1}$. Operating the pumps at an increased speed poses no engineering problems but the electrical power required increases as the cube of the velocity, i.e. 230 kW motors would be required to double the flow through each pump. The five impeller option has a total power requirement of 150 kW electric whereas three impellers operating at 25 $m^3 s^{-1}$ will require 420 kW electric and four impellers operating at 19 $m^3 s^{-1}$ will require 240 kW.

A very important implication of the entrainment flux is that it decreases the temperature of the discharge since the entrained water comes predominately from the hypolimnion. For a full reservoir the discharge temperature is expected to be in the range 17-18 °C and downstream temperatures will probably not exceed the +5 °C scenario shown in Figure 6. As the reservoir level falls, the discharge temperature will increase because of a lower entrainment flux.

Because the outlet is located adjacent to the bottom of the reservoir, operation of the pump is likely to resuspend sediment from the bottom. Presumably, the resultant elevated suspended sediment content of the discharge should persist for a relatively short period, i.e. the time it takes for the bottom to be scoured back to bedrock. Afterwards, no increase in suspended sediment content is anticipated. During the scouring period of operation, it may be wise to bypass the hydroelectric station to reduce abrasive wear on the turbine.

Preliminary estimates for a TVA-type surface pump system indicate a cost of AUD $250,000 per system. This does not include adding or modifying the electricity supply to the outlet structure or modifications to the outlet tower required for the attachment of the pontoons. Total capital cost of the system should be less than $2m which includes a $750,000 contingency component to cover modification to the power supply and outlet works.

10.5.2 Draft tube mixer

The draft tube mixer offers one distinct advantage over the surface pump – higher discharge temperatures for the same power requirements. On the other hand, the addition of the draft tube increases the capital cost. Also, this sort of mixer must be considered experimental as such a design has never been built or tested in an environment with strong horizontal velocities as water approaches the outlet.

The proposed design is similar to the surface pump design, but with a collapsible draft tube attached to the bottom of each pontoon and extending to 5-10 m of the top of the outlet, i.e. to 319 m AHD. A collapsible draft tube is required to accommodate changes in reservoir level. To the best of my knowledge, this sort of draft tube has never been constructed or tested. The draft tube prevents entrainment of cold water as the jet propagates towards the bottom. The lower entrainment flux demands that the pumps be capable of passing the entire reservoir discharge so five 15 $m^3 s^{-1}$ pumps will be required. Entrainment of ambient water along the 5-10 m distance between the bottom of the draft tube and the outlet will be very small and the discharge temperature can reasonably be expected to be within 1 or 2 °C of the surface layer temperature, i.e. a release temperature of 22-24 °C is expected.

The draft tube mixer design also allows the possibility of further operating cost savings by increasing the number of pumps and decreasing the flow through each pump. For example, a system with 8 pumps operating at 10 $m^3 s^{-1}$ would have a maximum total power consumption of 75 kW electric, i.e. less than half the power consumption of the 5 mixer system.

The cost of this system is calculated by adding the cost of the draft tubes to the cost for the surface pump system. Cost for the draft tubes are estimated to be $35,000 each. Total cost for the system is budgeted at $2.2m which includes a $750,000 contingency component. Note also that draft tube mixers use a different impeller design and therefore the surface pump system cannot be retrofitted with draft tubes without also replacing the impellers.

The operating costs of several impeller system configurations is shown in Table 4. These costs assume all of the discharge passes through the pump in order to maximise the temperature of the release and therefore are appropriate for the draft tube mixer. Because of entrainment, a simple surface pump system for Burrendong Reservoir only requires three 30 kW impellers.

Table 4 Monthly operating (electricity) costs for several surface pump configurations. Power is the electric power required for each impeller. Estimates based on actual releases during spring and summer are shown as 'Sep-Mar' discharge and are shaded. Discharges of 45 and 75 $m^3 s^{-1}$ assume continuous operation at the specified discharge. 'DT' denotes draft tube mixer.

Discharge ($m^3 s^{-1}$)	# impellers	Power (kW)	Monthly operating cost
45	3	30	$7400
75	3	280	$66753
75	4	60	$19233
75	5	30	$12105
Sep-Mar	3	30	$4435
Sep-Mar	3 (DT)	280	$10400
Sep-Mar	4 (DT)	60	$7100
Sep-Mar	5 (DT)	30	$6400

10.6 Submerged curtain

The location of the outlet works in a fairly protected embayment of the reservoir makes the submerged curtain option a feasible alternative. The curtain should attempt to seal along the bottom and sides with the upper edge of the curtain suspended 6 m below the water surface from a line of floats on the surface. As the water level drops, the top of the curtain is maintained at a depth of 6 m with surplus curtain material piling up on the bottom. As the reservoir fills, the curtain simply lifts up off the bottom.

To keep drag forces on the curtain tolerable it is advisable to deploy the curtain in a 3-sided configuration about 400 m away from the outlet. At the maximum design flow of 85 $m^3 s^{-1}$, this will ensure that velocities across the curtain don't exceed 20 cm s^{-1} significantly. There are insufficient data to assess the impact of currents induced by internal wave activity. Although it is unlikely that these will cause a problem, they should be considered in a more formal design.

In addition to drag forces on the curtain, there will be a distributed load arising from the density difference due to the temperature change across the curtain. At the bottom of the reservoir where this effect is the strongest, the curtain will be subjected to a pressure load of about 720 Pa.

The submerged curtain is expected to deliver consistently higher discharge temperatures (20-23 °C) during spring and summer than the unconfined surface pump option because, in theory, only water from the top 6 m is allowed into the vicinity of the outlet structure. However, it is possible that some colder water will leak in from around the sides and bottom of the curtain. Also, some heat will be lost from the water contained within the curtain due to thermal conduction through the curtain itself.

The amount of surface layer contaminants discharged from the reservoir using the curtain option is unknown. The volume of the withdrawal region inside the curtain is approximately 3770 ML, about the same as the average daily discharge. This means that the average downwards velocity of the water column will be about 30 m d^{-1}, much greater than typical floating speeds for cyanobacteria, and so one might expect the cyanobacteria to be discharged. However, it is possible that the withdrawal region may stratify diurnally (or persistently) and that some (or all) of the buoyant cyanobacteria present may remain within a surface layer. There are no data on the stratification dynamics of a withdrawal region for a system such as the one proposed here. Should a prototype system be deployed it would be highly desirable to ensure adequate monitoring and assessment of its hydrodynamic characteristics.

An estimate of the cost to install a submerged curtain is provided by extrapolating from the experience of the US Bureau of Reclamation (USBR) at Whiskeytown Reservoir. Their Spring Creek Tunnel Intake curtain cost USD $1.8 m and uses a very similar design to that proposed for Burrendong Dam; the overall dimensions are nearly identical. Also, the peak discharges are nearly the same for both systems so the Burrendong Dam application can be considered to be another application of a successful design. Assuming an exchange rate of AUD 1$ = USD $0.59 gives a cost of AUD $3 million. The material cost alone for an EPDM curtain (EPDM has superior longevity compared to HDPE) is likely to be $0.5m. The material has a life expectancy of 50 years. Fabrication and installation is likely to take at least 4 months (based on USBR experience) and is assumed to add no more than $2.5m to the total installed cost. Maintenance costs are expected to be less than experienced in the US because the Burrendong Dam curtain will be submerged and most wear requiring maintenance in Whiskeytown Reservoir was caused by surface wave action (Vermeyen, pers. comm.).

10.7 Caveats and recommendation

The analysis presented here considers only the need to increase the temperature of the discharge without any loss of hydroelectric generation. Because each of the 3 alternative methods cause surface layer water to be released it is important to recognize that any blue-green algal contamination in the reservoir near the outlet will be released downstream as well. This may or may not pose a problem. Unfortunately there is little direct evidence regarding downstream contamination by cyanobacteria released from dams. Whether or not the cells (colonies) can survive passage through the extremely turbulent environment of hydroelectric turbines and needle valves and continue to thrive in a flowing riverine environment requires further study.

The surface pump and draft tube mixer options allow greater operational flexibility because they allow a do nothing option. On the other hand, the simplicity of the submerged curtain (no moving parts) is attractive. The submerged curtain option does not allow the possibility of releases from the cold hypolimnion should these for some reason be desired, e.g. to avoid discharging blue green algae downstream.

Should a demonstration project be pursued, it will be necessary to allow 8 months for design, construction and deployment of a mitigation system. A further 2-3 months should be allowed for compliance testing and fine-tuning of components and design. Given these lead times, actual field trials cannot realistically be expected prior to spring 2001.

The recommended option is for the draft tube mixers. The initial capital cost is only about 20% greater than for the three surface pump option and it provides significantly warmer discharge temperatures benefiting hundreds of extra kilometres of river. Although each of the three options is feasible, the draft-tube mixers appear to provide the best price-performance ratio.

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