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Review of Temperature Control Options for Reservoir Release Flows

Research and Development Office
Prize Competition Program

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14. ABSTRACT Reclamation currently employs selective withdrawal devices and operational techniques at many facilities to meet downstream temperature requirements. The purpose of this document is to review existing temperature control options for controlling reservoir release temperatures, develop partnerships, identify subject matter experts, and recommend future actions. A Technology Search is recommended as a next step to seek industry cross-cutting ideas on water temperature control. Depending on the results of the Technology Search, a multi-stage prize competition may be pursued.			
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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Disclaimer

Cover Photo: Bureau of Reclamation's Shasta Dam on the Sacramento River was retrofitted with a selective withdrawal system to manage powerplant release water temperatures.

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Introduction

Reclamation must address temperature control of reservoir release flows to comply with water quality requirements and biological opinions, and to reduce potential impacts to species protected under the Endangered Species Act. Reclamation currently employs selective withdrawal devices and operational techniques at many facilities to meet downstream temperature requirements.

Dams can greatly influence downstream riverine temperature regimes. Water stored behind high-head dams can become thermally stratified, meaning that there is warmer water layer at the top of the water column (epilimnion) and cooler water at the bottom of the water column (hypolimnion). These layers are separated by a metalimnion (also called a thermocline) which limits normal convection circulation and prevents the hypolimnion from being mixed. The temperature can vary significantly from the water surface to the reservoir bottom. Fixed-flow release locations at a dam can only withdraw water at certain elevations and this can affect water temperature and quality of releases during certain times of the year. Released water may be too warm or too cold for optimal habitat and survival of fish species.

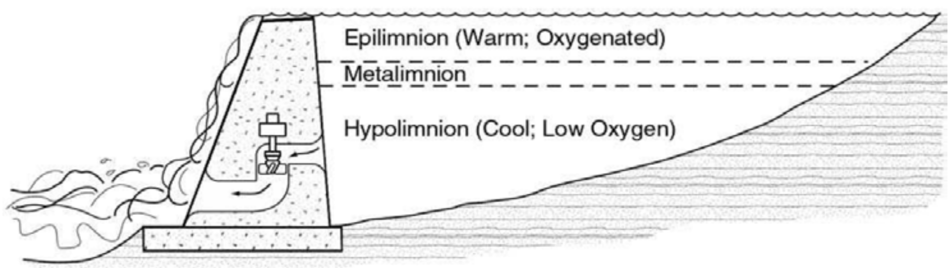

Figure 1. – Schematic of thermally stratified reservoir (Peterson et al. 2003).

Reclamation currently uses gated selective withdrawal devices at Shasta, Folsom, Hungry Horse, Flaming Gorge, and Jordanelle Dams to provide the ability to selectively withdraw water through outlets or gates at various elevations in the water column to address both warmer and colder water needs downstream. Reclamation also uses flexible temperature curtains in Whiskeytown and Lewiston Reservoirs to control mixing and provide for withdrawal at a specified elevation. Reclamation is currently exploring the efficacy of a temperature control device at Glen Canyon Dam to respond to potential extremes in hydrologic conditions that could result in nonnative fish establishment. The temperature control device would need to provide both warming and cooling of the river for high and low flow discharge scenarios for a wide range of reservoir levels (LTEMP 2016, Reclamation 1997, U.S Fish and Wildlife Service 1994, Vermeyen 1999).

Dam operation techniques are also used with and without physical temperature control devices to enhance benefits such as water supply and/or hydropower while simultaneously achieving release flows that meet temperature and water quality requirements. Predictive water temperature models are employed by Reclamation to assist with operational decisions at specific dams or for a basin-wide system of water storage reservoirs (e.g. California's Central Valley Project). Reclamation also employs various types of selective withdrawal systems for other reasons such as acid mine drainage, dissolved gas, phosphorous, turbidity and taste/odor (Vermeyen and DeMoyer 2003), but applications outside of temperature control will not be discussed in this report.

Reclamation's Research and Development Office is considering running a prize competition on temperature control of reservoir release flows (https://www.usbr.gov/research/challenges/). Prize competitions utilize citizen solvers and crowdsourcing to solicit solutions for difficult mission-centric problems. Temperature control of reservoir release flows was listed as a high-priority research need during the multi-agency Water Prize Competition Center workshop in the Ecosystem Restoration theme area in October 2014. Commissioner Lopez stated that this topic was an agency priority during a briefing in December 2014. An ongoing roadmapping effort for the Science and Technology (S&T) Program on "Environmental Issues for Water Delivery and Management (EN)" has identified the control of water temperatures downstream of dams as a topic of research interest (EN1 topic number 4, EN3 topic number 2).

Purpose

The purpose of this document is to review existing temperature control options for managing reservoir release temperatures, further support efforts to seek unapplied technologies related to temperature control, develop partnerships, identify subject matter experts, and recommend future actions. Results will help inform the state-of-practice and current limitations related to temperature control of reservoir release flows. Results can help better define the problem, identify known technologies, and focus the scope of a prize competition and the technical requirements needed for a successful solution.

Methods

A partial literature review was conducted to better understand how reservoir releases can be managed for water temperature. Existing devices and operational techniques currently employed at Reclamation facilities and other federal and non-federal facilities have been documented and innovative concepts in literature have been identified; however, this document is not exhaustive.

The literature review consisted of technical documents, guidelines, research studies, theses, and articles relating to temperature control of reservoir release flows. Interviews with Reclamation operators, engineers, and researchers and meetings with representatives of the Glen Canyon Dam Adaptive Management Work Group were conducted. This document does not focus on why temperature control is needed or the effects of temperature control devices and methods. The focus is on structural devices and operational techniques that can be used to modify flow regimes from reservoirs. Several future approaches are considered, such as development of analytical tools and/or numerical models, development of field research studies, pursuit of specific innovative or conceptual ideas, and/or creation of a prize competition to seek creative out-of-the-box solutions from the public.

Partners were sought within Reclamation and with other federal and non-federal entities facing similar issues with temperature control. If a prize competition is pursued, partners will be asked to participate in future design and judging of the prize competition.

A few reports provided extensive review of temperature control alternatives both in general and relating to site-specific applications. These reports are heavily credited throughout this review. Dr. Bradford Sherman (2000) provided a comprehensive review of engineering methods for the mitigation of cold water pollution downstream of dams in the report "Scoping Options for Mitigating Cold Water Discharges from Dams". His report outlines six devices and methods for addressing cold water pollution and provides a summary of pros and cons and costs for each method. The Glen Canyon Dam Value Planning Study (Reclamation 1997) outlined seven proposals related to controlling the temperature of release flows to enhance downstream fish habitat.

Alternatives

Gated Selective Withdrawal Systems

Gated selective withdrawal systems are typically rigid steel structures on the upstream face of the dam to enclose the penstock intakes. Gates at multiple elevations can be opened and closed to release water from various elevations in the water column depending on temperature needs in the downstream river channel. Selective withdrawal systems can be new external-frame structures that are attached to the dam or retrofit modifications to existing dam features, such as adding gates to the trashrack structure around the penstock intakes.

In 1996, a temperature control device was installed at Shasta Dam, a 602-ft-high concrete arch dam north of Redding, California. The temperature control device provides selective withdrawal of reservoir water into the Sacramento River. A 250-ft-wide by 300-ft-high selective withdrawal structure is attached to the upstream face of the dam and consists of a steel frame with multiple gates enclosing all five penstock intakes (elevation 815 ft). Gates are located at three levels (upper gate elevation 1,000-1,045 ft, middle gate elevation 900-945 ft, lower gate elevation 804-831 ft) and a lower-level, deep-water intake with side gates located at elevation 750 ft. This 8,000-ton structure allows water to be drawn from higher in the water column in the spring and early summer such that deeper, colder water can be conserved for release in the late summer months to protect downstream fisheries. The selective withdrawal structure passes water through the penstocks to the generators to maximize power generation. The system was costly to construct ($80 million, Hanna et al. 1999). Although maintenance costs have been low, needed repairs and retrofits have been costly.

Although this massive structure is effective at managing the reservoir release temperatures, shortcomings in the availability of the cold water pool due to low snowpack and drought can make it difficult to reliably meet downstream temperature goals. Temperature forecasting models and temperature decision support tools can be used to inform operation of the structure by anticipating the need for management actions and helping predict effectiveness of different real-time operations options (Bartholow et al. 2001).

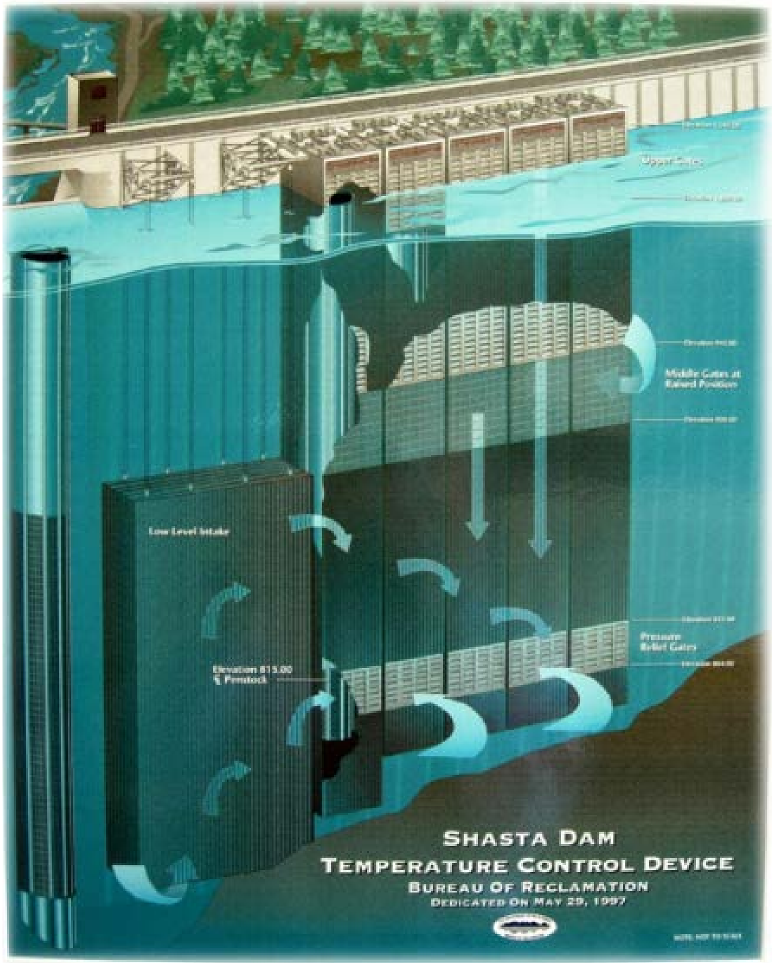

Figure 2. – Schematic of Shasta Dam selective withdrawal system.

In the late 1960s, Reclamation designed a modification to the trashrack structures at Folsom Dam on the American River north of Folsom, California, to permit selective withdrawal from higher elevations in the reservoir. Steel guides were attached to the existing trashrack panels with 45 steel shutter panels (9 per bay) operated by the gantry crane. The selective withdrawal performance of the shutters has been marginal because of leakage and difficulty in adjusting the shutters as the water surface drops throughout the summer and fall. Furthermore, debris accumulation in the shutter guides has been an operational problem since the shutters were installed upstream of the trashracks. Modernization of the temperature shutters on the penstock intakes at Folsom Dam has been identified as a potential solution to improve downstream water temperatures in the lower American River. A Value Planning Study was completed in 2014 to assess alternatives for reducing shutter leakage, providing flexible withdrawal above the penstocks, and providing withdrawal of cold water below the penstock intakes (Reclamation 2014).

Figure 3. – Folsom Dam temperature control shutters on Unit No. 1 trashrack.

In the late 1990s, a selective withdrawal structure was installed around an 84-inch-diameter municipal and industrial water supply intake at Folsom Dam to conserve cold water resources. The system consisted of three telescoping hoist-operated gates to allow for withdrawals over 70 feet of the water column (Vermeyen 1997). Additionally, Reclamation is currently requiring El Dorado Irrigation District to install a temperature control device for the raw water intake to El Dorado Hills Water Treatment Plant to conserve the cold water pool in Folsom Lake. Reclamation is providing federal funds to offset some project costs. The District's five existing raw pump casings will be replaced with four 36 in-diameter pipes with inlets at 3 different elevations.

Jordanelle Dam releases water through a selective level outlet works intake tower which consists of six gates at various elevations. A low-level intake structure with a bulkhead isolation gate is located 128 ft deeper than the lowest selective level outlet works gate opening (U.S. Department of the Interior and Central Utah Water Conservancy District 2005). By withdrawing water from different water depths using these two systems, Jordanelle Dam can control temperature, phosphorus, and dissolved oxygen levels released from the reservoir to help improve water quality in the middle Provo River, Utah.

In 1978, large steel selective withdrawal structures were retrofit to the dam face to surround the penstock inlets to manage downstream water temperatures at Flaming Gorge Dam (Peters 1978). The three gated intake structures allow near surface withdrawal during the summer and fall to increase the release water temperatures. The selective withdrawal gates must be submerged at least 40 ft below the water surface to avoid vortices that can entrain air into the penstocks. The approximate cost of the system was $4.6 million in 1978 (Burgi 1995).

Figure 4. – Photograph of the selective withdrawal structures on Flaming Gorge Dam, Utah.

In an effort to increase release water temperatures, Reclamation designed and constructed an adjustable semi-cylindrical bulkhead system within the power intake trashrack structures at Hungry Horse Dam in northwestern Montana on the South Fork of the Flathead River in 1995 (Kubitschek 1994 and Vermeyen 2006). Each telescoping gate system is made up of three gates (control, stationary, relief) which travel along the existing bulkhead guides. Near-surface withdrawals were required for reservoir water surface fluctuations up to 160 ft below the maximum water surface elevation. Adjustable bulkheads block deep cold water entry into the penstocks to allow withdrawal of warmer water for downstream release. However, low-level relief gates can be raised to withdraw directly into the penstocks during times when the reservoir is isothermal to minimize head loss. The approximate cost of the retrofit was $6.4 million (Burgi 1995).

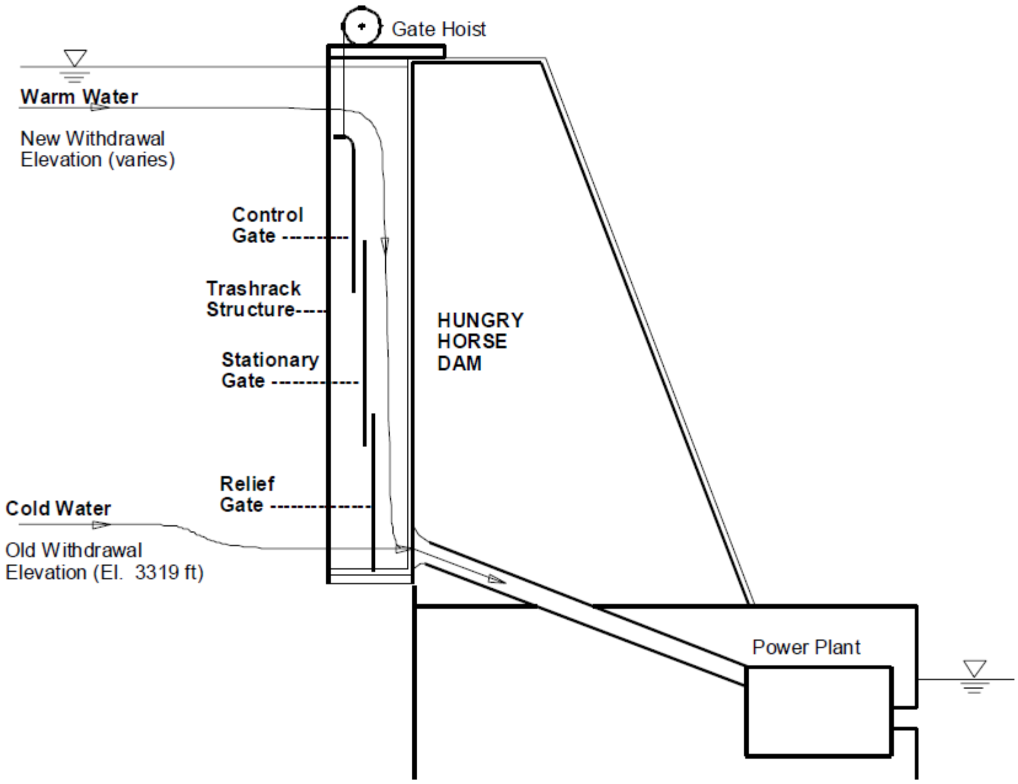

Figure 5. – Sectional view of Hungry Horse Dam selective withdrawal system (Vermeyen 2006).

The U.S. Army Corps of Engineers (USACE) has constructed several gated selective withdrawal systems. Constructed in the 1960s, USACE's Cougar Dam on the South Fork McKenzie River released water at cooler temperatures in spring and summer and warmer temperatures in the fall and winter, thereby impacting Chinook Salmon migration. In 2005, USACE modified the existing 300-ft-tall cast-in-place concrete intake tower by adding adjustable weir gates and a wet well to provide selective withdrawal capability. Three vertical slots on the wet well are overlapped by adjustable weir gates which can slide up and down as needed. The total cost of the project was $50.5 million in 2005 (https://www.nwp.usace.army.mil/willamette/cougar/temperature/).

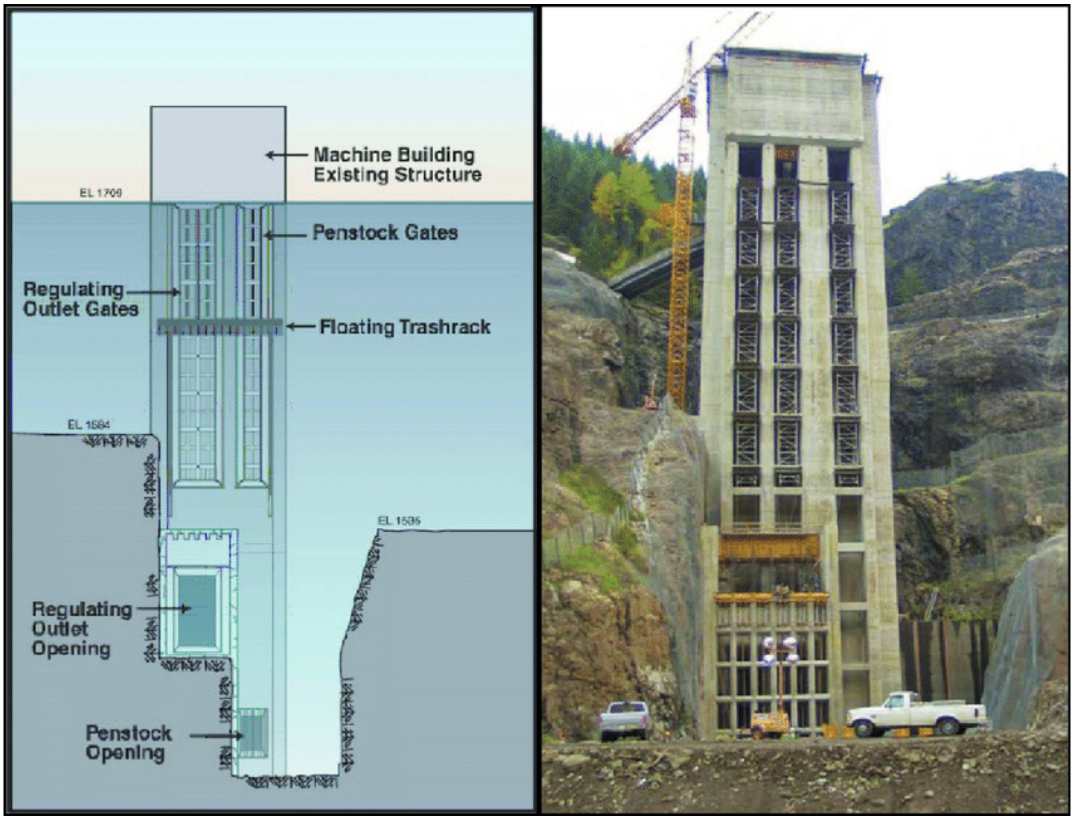

Figure 6. – Schematic and photograph of Cougar Dam temperature control tower (from USACE).

A selective withdrawal structure was built on top of the flood-flow regulating outlets at USACE's Applegate Lake, Rogue River Basin, Oregon. The selective withdrawal tower has five intake ports that allow water to enter one of two wet wells. USACE is planning to construct a 370-ft-high selective withdrawal tower at Detroit Dam with two high intake weirs for surface flow and four low intake gates to allow for temperature mixing. Details of other USACE dams with constructed selective withdrawal systems can be found in Vermeyen and DeMoyer (2003).

Fixed Flexible Temperature Curtains

Submerged curtains can be placed in a stratified reservoir to control release flow temperatures through an outlet or diversion. The vertical position, size, and orientation of the flexible curtain assists in controlling outflow temperatures. These types of temperature control devices are typically usable in shallower depths without strong currents. Temperature curtains can be most effective to prevent mixing at the inflow plunge zone, where colder water plunges beneath warmer surface water.

Two flexible curtains made of 60 mil Hypalon material were installed in Lewiston Reservoir, California in 1992. One curtain was designed to hold back warmer surface water while accessing colder water near the bottom for release to Clear Creek Tunnel and ultimately the lower Sacramento River Basin. The second curtain was designed to provide warmer surface withdrawals (when operating in overdraw mode) for Lewiston fish hatchery.

Two flexible curtains were installed in Whiskeytown Lake, California, in 1993 to provide greater temperature control in the Sacramento River Basin. Diverted water from Lewiston reservoir encounters a 40-ft-deep, 830-ft long temperature curtain that forces cooler inflows down to the bottom of the lake. A second 100-ft-deep, 2,400-foot long curtain sends cooler water into the Spring Creek tunnel. This curtain was replaced in 2011 and underwent repairs in 2017 due to wear. The expected life of the new curtain is projected to be about 15 years (www.project2105.org/TC/0612GS_WhiskeytownReservoir.pdf).

The gated selective withdrawal system at Folsom Dam allows cool water releases from Folsom Lake to be delivered to the lower American River. However, the temperature of the release flows can increase up to 3 degrees F because of mixing with warmer water in Lake Natoma, which is a shallow re-regulation reservoir formed by Nimbus Dam (Vermeyen 2005). As a result, flow releases from Nimbus Dam can be too warm for anadromous fish species. Vermeyen (2005) studied the potential for a temperature curtain within Lake Natoma to control mixing and reduce release water temperatures to the lower American River.

Reclamation also considered using a flexible temperature curtain for releases at Shasta Dam prior to construction of the fixed steel selective withdrawal structure. CH2M Hill proposed seasonal installation of a fixed series of reinforced Hypalon curtains upstream of the dam to draw cold water from the deeper part of the reservoir. Ultimately, a more traditional selective withdrawal structure was selected due to required curtain size, reservoir fluctuations, need for operational flexibility, and lack of experience with large curtain structures (Vermeyen 1997).

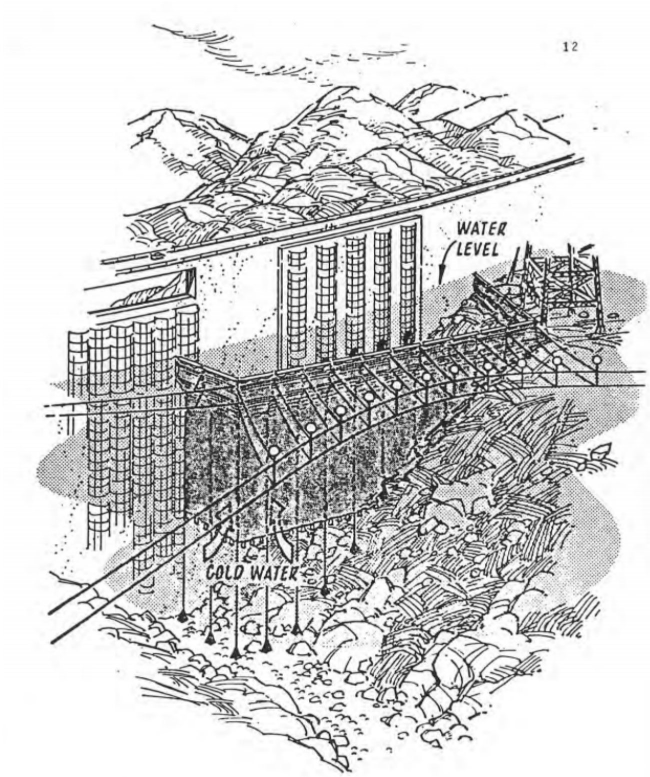

Figure 7. – Schematic of fixed flexible curtain concept for Shasta Dam cool water withdrawal (Johnson 1987).

Price and Meyer (1992) describe two similar fixed position structures that can be used to block the withdrawal of hypolimnetic water and allow the release of epilimnetic water: underwater dams (e.g. rock, sheet pile) and submerged skimming weirs.

Adjustable Flexible Temperature Curtains

Burrendong Temperature Control Structure at Burrendong Dam (New South Wales, Australia) was constructed in 2014 to reduce the effects of cold water pollution on native fish in the Macquarie River (www.waternsw.com.au/projects/burrendong). The estimated cost of the curtain was 3.4 million dollars (Australian). The flexible curtain surrounds the intake tower, submerged just below the water surface to allow warmer surface water to be released downstream through the outlet valve. A chain and pulley mechanism allows the curtain to be raised and lowered. The curtain failed due to flooding in 2016, but has been reinstalled with anchoring improvements. Sherman (2000) describes an alternative for Burrendong Dam with a submerged temperature curtain surrounding the intake tower.

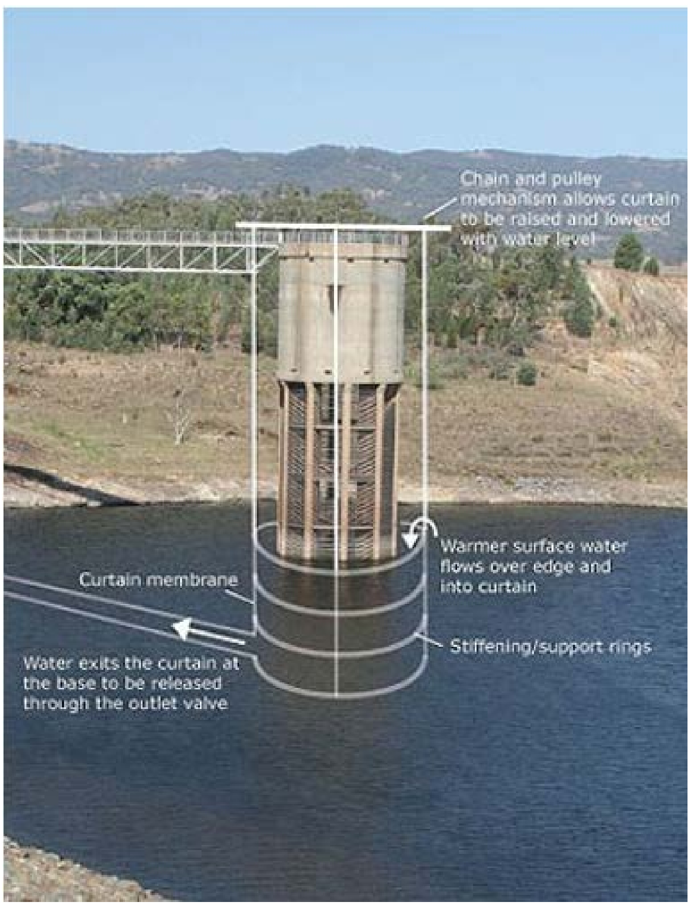

Figure 8. – Installed adjustable temperature control curtain at Burrendong Dam (www.waternsw.com.au/projects/burrendong).

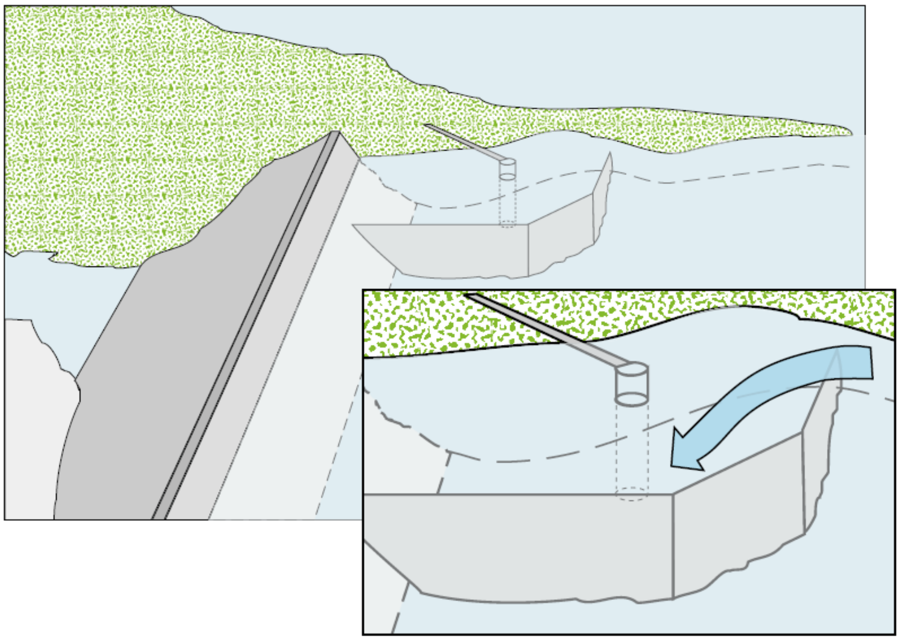

Figure 9. – Proposed submerged adjustable temperature curtain and outlet works at Burrendong Dam (Sherman 2000).

In the 1987 Shasta Dam Value Engineering study, an adjustable curtain-type temperature modification facility was proposed. The curtain would have surrounded the five penstock intakes and would have been adjusted to release water from the appropriate elevation in the water column. As previously described, a multi-level selective withdrawal structure was ultimately selected for installation.

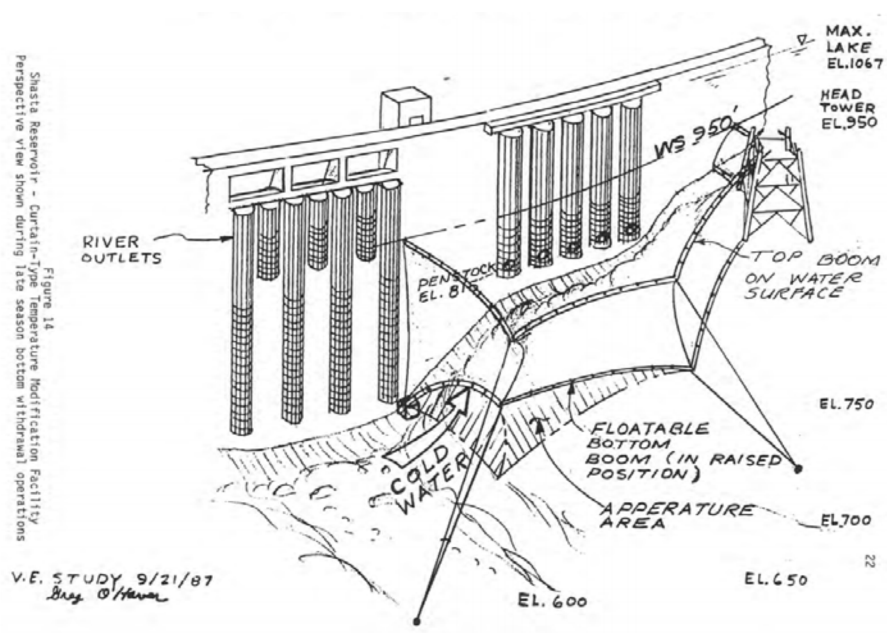

Figure 10. – Proposed adjustable flexible temperature curtain for Shasta Dam temperature control.

Destratification Devices

Destratification devices induce large-scale circulation or mechanical mixing within the reservoir to reduce the vertical temperature gradient of the water column upstream from the outlet structure. This is generally accomplished using bubble plumes or buoyant jets (Figure 11). Artificial circulation can also be induced with bottom diffusers or aerators that bring water from the hypolimnion up to the surface. Air-lift systems and bubble plume destratification systems utilize an air compressor to lift water up to the release outlet elevation.

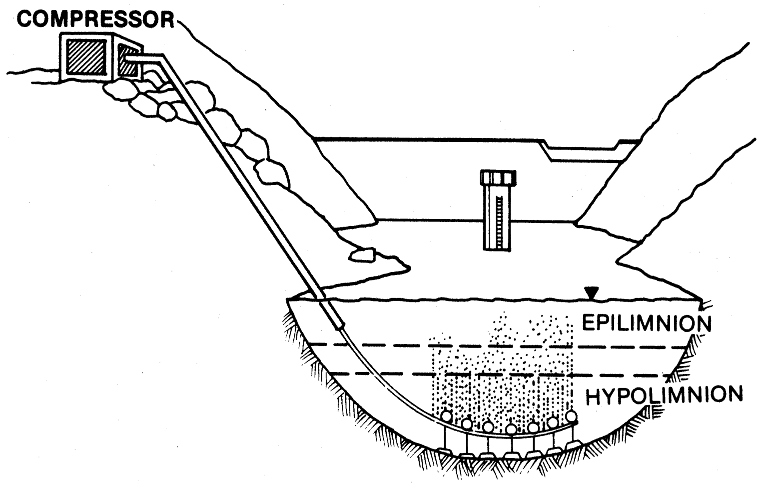

Figure 11. – Schematic of an artificial destratification system (from USACE).

Destratification can be effective for small-to-medium sized reservoirs (Sherman 2000). Feasibility decreases with increasing reservoir size. Sherman (2000) also notes that increased hypolimnion temperatures increase oxygen demand, nutrient release, and hydrogen sulfide production if not operated continuously from spring through autumn.

Experience with destratification (e.g. Chaffey Dam) confirms that an appropriately sized system can effectively raise reservoir temperatures (Sherman 2000). Local destratification has been used by Tennessee Valley Authority to reduce condenser cooler water temperatures at Belews Creek Fossil Plant (Sherman 2000).

Local destratification, also referred to as localized mixing, applies a similar principle on a smaller scale, thus making it a more cost-effective option for large projects. The main difference between general destratification and localized mixing is that localized mixing targets the water column directly upstream from the intakes, as opposed to the entire reservoir. Price and Meyer (1992) discuss the theory, methodology, and application of this technique. Some key parameters that must be considered in this localized application are the pumping to release ratio, penetration of jet, and size/quantity of mixing apparatuses.

An underwater power thruster was proposed at Shasta Dam in 1987 to lift cold water from the bottom of the reservoir through a conduit to the immediate vicinity of the penstock intakes.

Alternately, a "elephant trunk" conduit extending into the deepest part of the reservoir was also suggested (Johnson 1987).

Surface Pumps and Draft Tube Mixers

Surface pumps and draft tube mixers are top-down circulation approaches. Surface pumps send warm surface water down through the thermocline and into the withdrawal zone for the outlet works. Impellors are powered by electricity and the velocity of the jet increases as the pump speed increases. Draft tubes can reduce the amount of water entrained by the jet, thereby increasing energy efficiency of the surface pump.

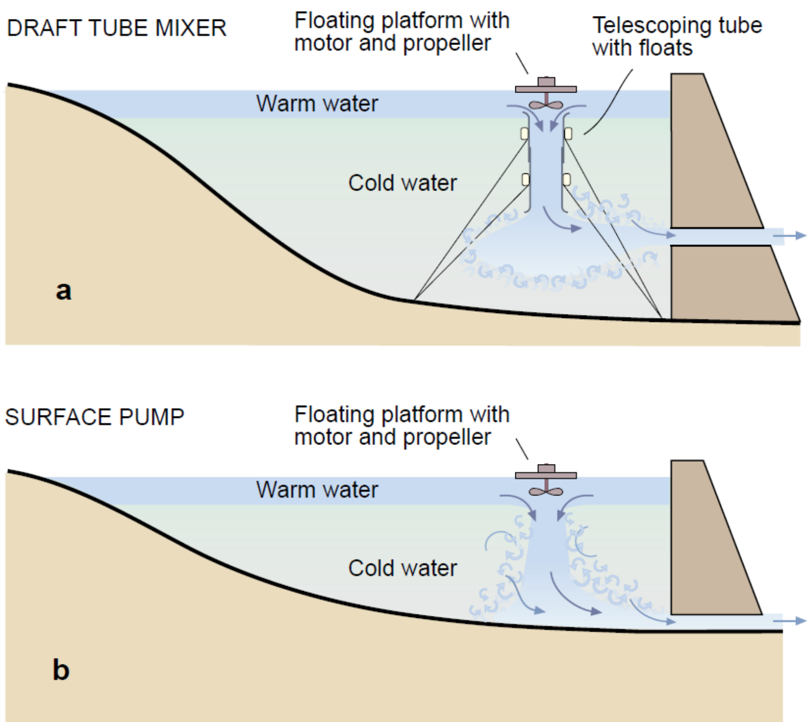

Figure 12. – Schematic of surface pump with draft tube (a) and basic surface pump (Sherman 2000).

These types of systems raise concerns about recreational safety; however, installing them near to the dam minimizes safety concerns. Also, debris can be entrained in the impellor and may become lodged if a draft tube is present causing blockage and inefficiency of the system. Disturbance and re-suspension of sediment can be a significant challenge in the application of this technique. These systems may consist of one large pump system (less maintenance and fewer moving parts) or several smaller pump systems (providing redundancy and efficiency in power consumption).

Warming Basins

Warming basins are large shallow water bodies that warm water via sun exposure prior to release into the river. Warming basins are typically not feasible due to the need for large tracts of land required for satisfactory warming.

In one example, the Oroville-Thermalito Complex is a group of reservoirs, structures, and facilities that functions as a regional water conveyance and storage system and the headwaters of the California Department of Water Resource's State Water Project. One feature of the system, the Thermalito Afterbay, serves several purposes, including functioning as a warming basin for agricultural water delivery to farms east of the afterbay (https://norcalwater.org/efficient-water-management/efficient-water-management-regional-sustainability/water-maps/oroville/). The afterbay has a maximum operating storage of 57,040 acre feet, a water surface area of 4,300 acres at maximum storage, and a maximum depth of approximately 20 feet.

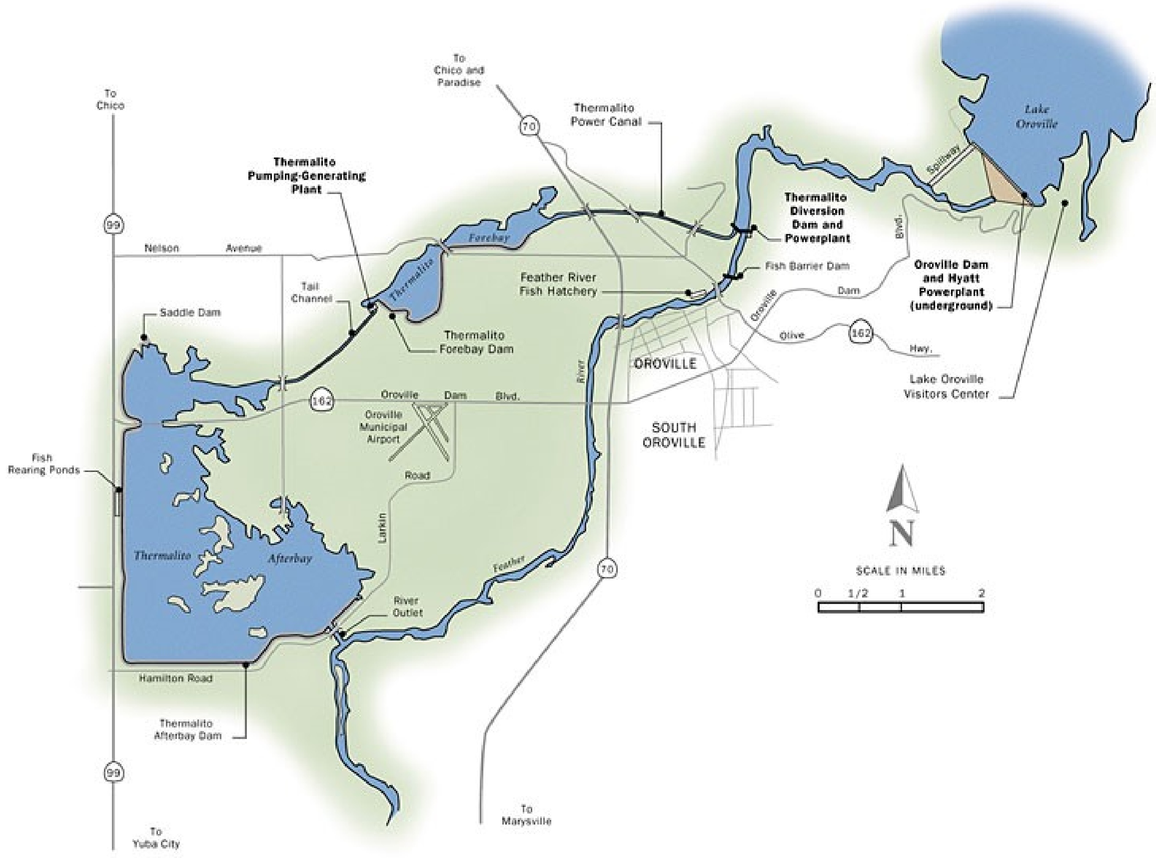

Figure 13. – Map of Oroville-Thermalito Complex ((California Department of Water Resources, https://water.ca.gov/Programs/State-Water-Project/SWP-Facilities/Oroville).

Floating Intakes

Floating intakes are pipes hinged such that the pipe intake can be positioned to draw water from different levels in the water column. The pipe may be connected to a float at the water surface to adjust the elevation of the pipe entrance. This technique may also be referred to as a trunnion intake structure as the floating pipes are generally hinged about a trunnion at the outlet point.

Sherman (2000) states that this technology is not suitable for large discharges (over 100 ML/d or 40.9 ft^3/s) because of the difficulty of constructing and operating large diameter submerged pipes. Deep reservoirs may require multiple trunnions which, in turn, would require multi-level outlet release points.

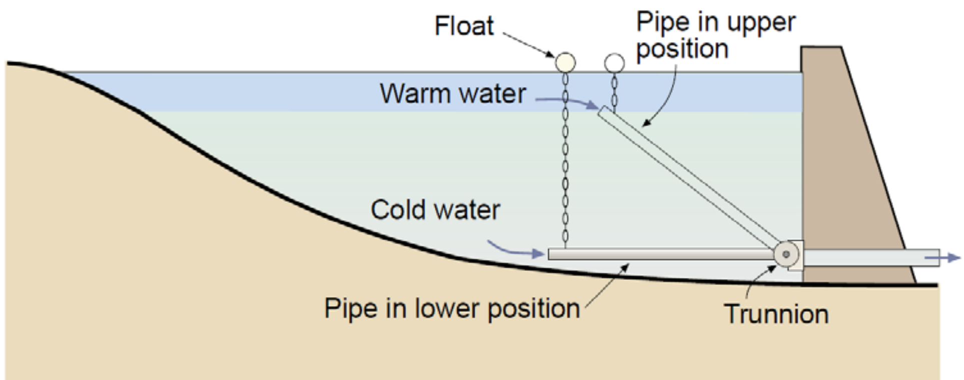

Figure 14. – Schematic of one type of floating intake design (Sherman 2000).

Multi-Level Outlets

Multi-level outlets allow release of flows through various elevations in the water column. Most dams would require a retrofit to add multiple fixed openings at several levels above the intakes. Multi-level outlet towers are common for embankment dams and usually require draining the reservoir to construct the structure. This approach is likely to be very expensive and may have dam safety implications.

Reservoir Fill and Release Strategies

Reservoir fill, circulation, and release strategies can also impact downstream temperatures. Price and Meyer (1992) reviewed several operational water quality enhancement techniques in addition to technologies already mentioned: guide curve changes, inflow routing, supplemental releases, concentration of flow through one gate, release strategy optimization, hypolimnetic withdrawal, and turbine venting. These types of reservoir operation strategies affect inflow residence time and routing, and release location and timing.

In the Shasta Dam Temperature Modification Value Engineering study (1987), continued releases through lower river outlets was recommended to provide lower temperature water downstream. However, the river outlet releases bypass the penstock and turbines, resulting in loss of power revenue. A concept to construct a bifurcation with one branch remaining a river outlet and one branch connecting to an existing penstock was proposed as a potential option for reducing power losses, but the concept was not further explored (Johnson 1987). The same Value Engineering study recommended installation of turbines in the river outlets to recover power revenue that would otherwise be lost. Turbine installation, however, could significantly reduce the existing capacity of the river outlets.

Since 2007, USACE has used a combination of spill operations (20 ft below conservation pool) and normal releases for hydropower generation (150 ft below conservation pool) to maintain target water temperatures downstream of Detroit Dam in Oregon. Warm and cool water mix in the pool between Detroit and Big Cliff dams. Water is released from Big Cliff Dam to meet the downstream temperature objective of creating optimal spawning and rearing habitat for spring-run Chinook Salmon and winter Steelhead (https://www.nwp.usace.army.mil/DesktopModules/ArticleCS/Print.aspx?PortalId=24&ModuleId=88292&Article=1552057).

Reservoir fill and circulation strategies could conceptually involve using adjustable temperature curtains installed at the main inlet of a reservoir to force warm inflow downward toward the hypolimnion of the stratified reservoir. If the jet below the curtain is strong enough it will circulate the water resulting in significant destratification. Producing a strong jet under a flexible curtain, however, will cause the curtain to flex under hydraulic loading. Curtains are typically designed to minimize underflow velocity. This concept may also not be feasible at larger reservoirs as there are likely many smaller tributaries and large storage volumes. The inflow may not generate enough velocity to effectively penetrate the hypolimnion or cause destratification at the outlet works, which is typically a considerable distance from the main tributary.

Unapplied Concepts for Large Stratified Reservoirs

Heat Exchange Devices

Heat exchangers transfer thermal energy between two or more fluids, typically to heat or cool a fluid stream. In a countercurrent heat exchange system, pipes carry flow in opposite directions of travel and heat is exchanged via conduction and convection. A typical countercurrent system will have fluid flowing from a heat source to a heat sink. Once the fluid has reached the desired location it begins a return flow path where it passes the fluid flowing from the heat source and thus heat is transferred effectively warming the cooler liquid via convection and conduction. This process is often found in natural biological processes. A typical parallel current heat exchange system works in a similar fashion but the fluids in the pipes run in the same direction. This can be envisioned as warm liquid from a heat source flowing in a pipe that touched cool liquid flowing from a heat sink flowing side-by-side. The cool liquid will absorb heat from the warm liquid via conduction and convection and eventually the liquids will reach an equilibrium state.

Cooling towers, falling film coolers, and pipe bundle-and-plate heat exchangers are used for the cooling of process water. For wastewater cooling, spiral heat exchangers and rotary heat exchanger E-plate are other alternatives (https://www.das-ee.com/en-us/wastewater-treatment/plant-optimization/temperature-control/). It is uncertain how heat exchangers could be applied to reservoir release flows for effective and economical temperature control, but the concept may hold some merit for this type of application.

Mechanical Cooling of Reservoir Outflow

Large-scale mechanical chillers or evaporative cooling units could be used to decrease reservoir outflow temperatures. Power requirements and costs for operating these units has prevented their application to date. In addition, heat waste and other environmental impacts must be considered. It may be possible for heat recovery systems to capture generated heat and use a portion of it for useful purposes.

In California's Central Valley, temperature control downstream of Shasta Reservoir affects survival of winter-run Chinook Salmon. When not enough cold water is available to provide adequate downstream temperatures for salmon, regulatory agencies will restrict Reclamation from allocating water to any other purpose. Concurrently, the growth of solar energy production in California has made mid-day power generation inexpensive and, on some days during peak solar generation times, "negative pricing" exists where it costs Reclamation to generate power. The combination of a strong need for colder reservoir release flows and the potential for use of mid-day power with limited impact to power revenue has raised interest by Reclamation, partners, and contractors in examining large-scale water cooling units to assist in regulating downstream river temperatures.

Liquid Air Energy Storage

Liquid Air Energy Storage (LAES) uses electricity (e.g. hydropower generated during off-peak hours) to cool air until it liquefies, stores the liquid air in a tank, brings the liquid air back to a gaseous state, and uses that gas to turn a turbine to generate electricity. The energy industry is seeking use cases for economical disposal of "waste cold" generating during the heating process. A proposal was recently submitted to Reclamation's Science and Technology Program to investigate using the waste cold from LAES to achieve downstream cold water temperature objectives (personal communication, Mike Wright, Mid-Pacific Regional Office, Division of Planning).

"Infinitely Flexible" Temperature Control Device

Investigations could be performed to determine if the concept of an infinitely flexible temperature control device can meet downstream temperature objectives. Structural devices have operational limitations such that water cannot be withdrawn from an exact temperature layer in a stratified reservoir. Temperature modeling could be used to determine if there is value in attempting to design a new type of system with significantly greater operational flexibility or if temperature objectives cannot be obtained even with infinite flexibility.

Limiting Reservoir Heating

Other types of concepts relate to preventing a reservoir from heating by limiting exposure to solar radiation or managing temperatures within the reservoir. Ideas may include covering portions of the reservoir with overhead shading or constructing artificial wetlands or floating vegetation islands.

A team of engineers from the University of Colorado Boulder has developed a manufactured metamaterial film that cools the object underneath by reflecting incoming solar energy while allowing the surface to shed infrared thermal radiation. The glass-polymer hybrid material is manufactured on rolls so it may be potentially viable at larger-scales (https://www.colorado.edu/today/2017/02/09/newly-engineered-material-can-cool-roofsstructures-zero-energy-consumption). Application of this type of technology to reservoir cooling is unknown.

Los Angeles Water and Power has covered reservoirs with "shade balls" to improve water quality and reduce evaporation (https://www.ladwpnews.com/mayor-garcetti-announces-completion-of-innovative-shade-ball-cover-project-at-los-angeles-reservoir/). This type of technology, or floating covers, may also be able to reduce reservoir heating.

Prize Competition Suitability

Competition Focus

The focus of a prize competition could be on novel devices or techniques for temperature control of reservoir release flows. Solutions could be at-dam or near-dam structural, mechanical, or heat exchange devices, reservoir fill or release strategies, or larger-scale reservoir management strategies for controlling release temperatures at dams. Competitors could be asked to submit ideas for technologies or strategies that can produce cooler water releases, warmer water releases, or both. Predictive water temperature models to assist with operational decisions at specific dams or for a basin-wide system of water storage reservoirs would be outside of the scope of the competition because inflow characteristics and release requirements are site-specific.

The competition design team will need to consider the following technical issues when determining how to design an effective prize competition:

- Size and depth of reservoir
- Outflow discharge range
- Typical stratified temperature profile
- Description of various types/designs of facilities in need of temperature control
- Required release temperatures (colder, warmer, or both)
- Allowable power requirements and overall cost
- Need for continuous adjustment or occasional adjustment based on daily or seasonal modifications to meet temperature goals
- Acceptability of making modifications to dam (e.g. pipes through dam or embankments) that may impact dam safety requirements
- Practicality and scalability
- Need to make data sets available to participants to highlight the dynamic reservoir conditions and temperature ranges upstream and downstream of a facility

Partners and subject matter experts were sought during this review. The Glen Canyon Dam Adaptive Management Work Group and the Sacramento River Temperature Task Group have alignment with this topic area.

Competition Approach

Technology Search

A Technology Search is a way to explore existing technologies, technologies under development, and technologies that may be cross-cutting across industries. Sources can be government, universities, research institutes, non-profit organizations, established companies, and small start-up companies on a world-wide scale. A Technology Search can align the seeker with companies and researchers that may not have been on their radar.

Reclamation can seek vendors to conduct a Technology Search through Reclamation's existing Interagency Agreement with NASA's Center for Excellence for Collaborative Innovation. A Technology Search typically costs around $30,000-$40,000 with a duration of about 4 months. Subject matter experts meet with the vendor about every 2 weeks to discuss progress and refine the search. At the end of the contract, the vendor provides a final report with recommendations on the most highly aligned technologies. Contact information is provided to broker relationships.

Through a Technology Search, the seeker may uncover an applicable technology worth pursuing or search results may help better define and scale a future prize competition.

Multi-Stage Prize Competition

This topic may be suitable for a multi-stage prize competition focused on technology development. Winning submissions may provide Reclamation and its partners with incremental improvements to current methods or even revolutionary advancements on this important challenge. However, this is a challenging and complex topic. Successful solutions are anticipated to require significant development and resources before a prototype field assessment at a large dam could occur.

For submissions with a low Technology Readiness Level, physical and/or numerical modeling would be needed to bridge the gap between theoretical concept and prototype testing. Mid-competition award vouchers could be used to pair participants with technical experts who can advance concepts through physical or numerical modeling, depending on which type of modeling is most beneficial.

Physical models of stratified reservoirs have been constructed and tested in Reclamation's Hydraulics Laboratory for the Whiskeytown and Lewiston temperature curtains and the Shasta temperature control device using chillers (Vermeyen 1997 and Johnson et al. 1991). This type of modeling has challenges, including consistency in creating stratified layers and repeatability of test runs. Saline water can be used to enhance stratification, but this experimental set-up would require a separate test facility due to mixed outflow. Numerical modeling is an option for structural devices, but thermodynamic solutions (e.g. temperature exchange devices, chillers) would require thermodynamic modeling and reservoir circulation and flow strategies would require large-scale three-dimensional hydrodynamic modeling.

For submissions with a higher Technology Readiness Level, a model or small-scale prototype may exist and some model testing may already have been conducted. Physical and/or numerical modeling may be of benefit to refine designs.

If multiple stages of competition are not appropriate due to the quantity or quality of submissions from the first stage, Reclamation may be able to further develop innovative concepts depending on the specialized expertise required. If submissions involve technologies outside of Reclamation expertise, partnerships will be required to further advance ideas.

A multi-stage prize competition could be structured in many ways. One type of prize competition architecture could be as follows:

Stage 1

- Theoretical white paper submission with discussion of concept and how the concept could be evaluated
- Award top 10 submissions

Stage 2

- Development of top 10 submissions through technical support by Reclamation or partners
- Video submission describing progress or small-scale technology demonstration
- Final award of top 3 submissions
- Further development through laboratory vouchers

Conclusions and Recommendations

Reclamation has few applicable tools to manage water temperatures at reservoir release locations. Reclamation has spent significant resources on the design, performance testing, and monitoring of selective withdrawal structures and temperature curtains to meet temperature objectives at various facilities. Major infrastructure modifications are expensive to build and maintain. Operations-based approaches have competing priorities and limited flexibility. More tools are needed to provide management techniques that are appropriate for specific applications. Interest in this topic is far-reaching within Reclamation.

A Technology Search is recommended as a next step to seek industry cross-cutting ideas. It is possible that existing technologies from other industries could be modified and scaled for application at Reclamation facilities. However, practicality and cost of applied technologies may be limiting factors. A Technology Search may assist in brokering relationships with researchers and companies with similar technologies in different fields, which would be useful to advancing Reclamation's interests.

After a Technology Search, a multi-stage prize competition may be warranted since it can be an effective way to move ideas more quickly through technology development. Subject matter experts within Reclamation and other interested agencies will be needed to further define the requirements for a successful solution to this problem. Providing prize awards for submissions that meet intermediate milestones and providing mentoring to assist with partner relationships and technology development can improve the likelihood of successful demonstration projects. Prize competition architecture for technology demonstration at a laboratory scale or field scale will require further discussion due to complexities with physical and numerical modeling and the large scale of Reclamation's stratified reservoirs.

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