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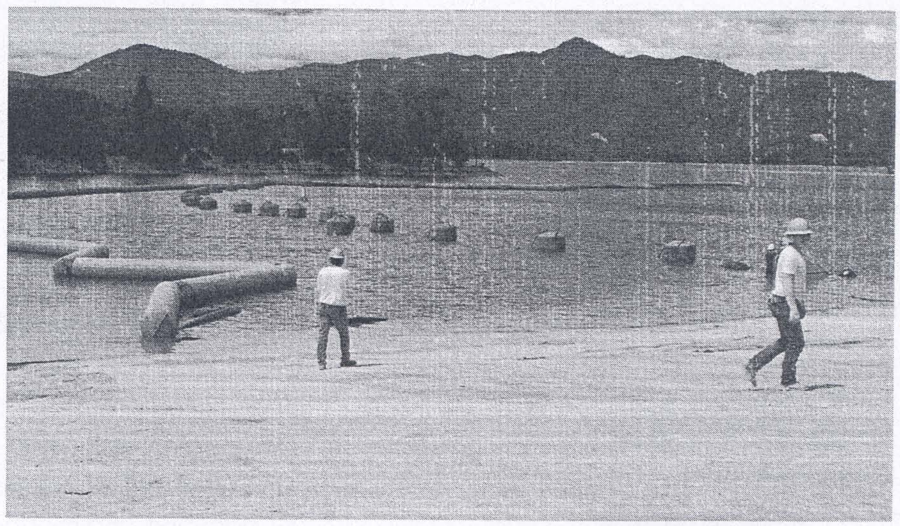
Managing Water Temperatures Below Hydroelectric Facilities

U.S. Bureau of Reclamation engineers have successfully lowered water temperatures downstream from hydroelectric facilities by using flexible rubber curtains. This innovative technology is aiding the survival of endangered fish populations.

By Perry L. Johnson, Tracy B. Vermeyen, and G. Greg O'Haver

Drought-related water temperature problems posed threats to endangered fish populations in the waters below the U.S. Bureau of Reclamation's hydroelectric power plants in the northern California Central Valley Project in the early 1990s. As an interim solution, the agency bypassed water from the plants during critical periods, at a cost of some $10 million in lost power revenues.

Concerned that traditional methods of reducing downstream water temperatures would require expensive modifications to projects' civil works, Reclamation engineers developed an alternative. They designed lightweight and flexible curtains made from a rubber-like material for installation in the project reservoirs and waterways. The curtains—which can be included in the design of new projects or retrofitted to old ones—allow project operators to manage reservoir flows and power withdrawals to reduce the temperature of water releases. The flexible reservoir curtains are effective in reducing downstream temperatures and have substantial economic benefits compared with traditional selective-withdrawal methods.



Surface buoys shown in this photograph support the flexible curtain installed at the U.S. Bureau of Reclamation's 154-MW Judge Francis Carr Hydropower Plant to prevent withdrawal of high-temperature surface water that was endangering fish populations downstream of the project.

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Identifying the Effects of High-Temperature Water

During the late 1980s, extended drought in northern California created a potentially dangerous situation for salmon and other fish in the Sacramento and Trinity rivers. Summer and early fall river-water temperatures threatened to exceed critical levels for sustaining salmon populations in both rivers. Reservoir storage had been low, and volumes of stored, cold water were limited. In 1992, a critical low-water year, the situation worsened. High water temperatures in the reservoirs, coupled with natural in-river warming from weather effects, threatened to make downstream waters too warm for egg incubation and juvenile fish survival. Consequently, Reclamation engineers began an aggressive program of constructing reservoir features that would allow cold water releases.

The Central Valley Project includes the 154-MW Judge Francis Carr Hydropower Plant and the 180-MW Spring Creek Hydropower Plant. Figure 1 shows the layout of Reclamation's Central Valley Project and the water path

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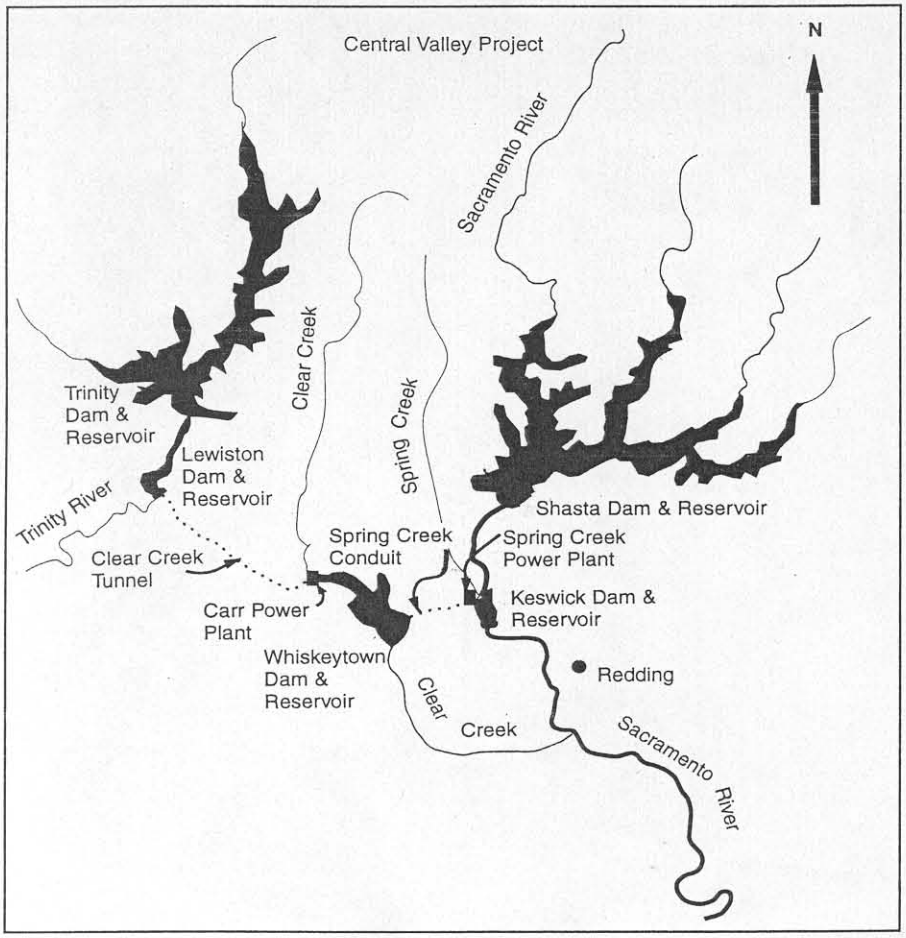

Figure 1: U.S. Bureau of Reclamation engineers designed flexible curtains to manage water temperatures downstream of hydroelectric facilities at the Central Valley Project. As illustrated in this map, water from the Trinity River is diverted at the project's Lewiston Dam. The water passes through the Clear Creek Tunnel to 154-MW Judge Francis Carr Hydropower Plant and into Whiskeytown Reservoir. From there, water flows through the Spring Creek Conduit to 180-MW Spring Creek hydro plant, then into Keswick Reservoir and finally to the Sacramento River.

through which Trinity River water reaches the Sacramento River. The Lewiston and Whiskeytown reservoirs downstream from Trinity Reservoir are where Reclamation engineers chose for flexible reservoir curtain installations.

When a reservoir is thermally stratified, or has variable temperatures from top to bottom, water can be withdrawn from distinct horizontal layers or elevations. The vertical position and thickness of the withdrawal layer depends on several factors:

— Placement, size, and orientation of the intake;
— Frequency of the withdrawal discharges;
— How warm or cold the water is at different levels;
— Topography of the site and dam; and
— Boundary interference from either the reservoir water surface or bottom.

The constraints on the upper and lower bounds of the withdrawal layer were defined by U.S. Army Corps of Engineers and other researchers who conducted detailed laboratory studies between 1969 to 1985.[1,2,3] Typically, these studies used laboratory models with simplified intake and reservoir configurations.

Site-specific configuration influences, however, are not addressed by basic temperature-stratification theory. Thus, variations from withdrawal-layer bounds predicted by theory can be expected. If reservoir configuration is restrictive or if intake design is unusual, temperature-stratified physical models should be used to evaluate selective withdrawal performance and to refine structural design.

To develop the strategy for the Central Valley Project, Reclamation engineers used physical models to determine both reservoir and river responses to curtain installation. In addition to this research, Reclamation engineers conducted a value engineering study on how to provide cost-effective, alternative selective-withdrawal options. Through this study, they determined that flexible reservoir curtains clearly offered potential cost benefits.

Implementing Lewiston Reservoir Research

The 91-foot-high Lewiston Dam and its reservoir regulate water releases from Trinity Reservoir downstream to the Trinity River. Lewiston Reservoir also is a diversion pool for the Clear Creek Tunnel intake from which Trinity River water eventually flows into the Sacramento River. (See Figure 1.) The reservoir has an active volume of 14,700 acre-feet and a maximum depth of 65 feet. Maximum combined summer releases from the reservoir are about 3,700 cubic feet per second (cfs).

Reclamation engineers created a model of Lewiston Reservoir in the agency's Water Resources Research Laboratory at Denver. The model scale was chosen to examine, in a limited laboratory space, potential curtain locations and site topography that critically influence water-withdrawal temperatures. Once the model was completed, engineers studied the potential effectiveness of two flexible-curtain structures to reduce temperatures in water diverted into Clear Creek Tunnel.

Although the Lewiston Reservoir model could not accurately predict turbulent mixing of reservoir contents, the model was tested to generate qualitative results. Elements of the study included evaluating withdrawal-layer temperatures, velocity profiles at several reservoir cross sections. The study also looked at the resulting modifications to temperature stratification at the Clear Creek tunnel intake made possible by several engineering options for curtain location, curtain length, and curtain depth. Both the reservoir and intake locations were modeled.

In general, the model data indicated that intake and reservoir curtains would be effective in cooling the water released from the reservoir. Curtain effectiveness depended on design, location, discharge, and topographic effects. At high discharges of 2,500 to 3,700 cfs, stratified flow through the "narrows"—a restricted portion of the Lewiston Reservoir—caused mixing with substantial warming of release water. Locating the reservoir curtain upstream from the narrows controlled warming by limiting the available warm surface water to the voir. As a result, flows are routed through the deep, cold-water zone of the reservoir. Two flexible curtains, a tailrace curtain at Carr power plant and an intake curtain at Spring Creek plant, were installed in Whiskeytown Reservoir.

Installing the Tailrace Curtain

Cold water from the Carr plant enters Whiskeytown Reservoir and pushes warm surface water ahead of the cold inflow. As the reservoir cross section increases, the in-flowing cold water velocities decrease, and the heavier and denser cold water plunges under the warm surface water. From this plunge point, an extended layer occurs in which the top of the cold water inflow mixes with the bottom of the warm water layer above. The extent of this mixing zone is exaggerated by the long, narrow inflow channel. Reclamation engineers developed a tailrace curtain that holds back the warm surface water and allows cold water inflow to the cold-water zone. With the tailrace curtain in place, limited mixing occurs.

Engineers used a 1:72 scale physical model to determine optimum placement and size of the curtain. They ensured that the cold inflow was introduced at sufficient depth and at low enough velocities to minimize mixing. The model study indicated that a 600-foot-long, 40-foot-deep tailrace curtain suspended from the reservoir surface should be installed 1.5 miles downstream from Carr plant at a section approximately 90 feet deep.

In the spring of 1993, construction crews installed the tailrace curtain at the Carr plant in a similar design to the Lewiston Reservoir curtain. The tailrace curtain was designed for removal in the winter when storm runoff occurs with heavy debris loads that could damage the curtain. Because Whiskeytown Reservoir is a popular recreation area, engineers designed the top of the tailrace curtain with a 16-foot-wide, 6-foot-deep opening through which boats can pass. Warm water leaking through the boat passage has an adverse effect on curtain performance. Engineers are evaluating potential solutions such as a gated boat channel around the curtain. Crews fabricated and installed the tailrace curtain in one month at a cost of $500,000.

Installing the Intake Curtain

The intake for the Spring Creek Hydropower Plant sits in a bowl located above the deepest portion of Whiskeytown Reservoir. Temperature profiles collected in the reservoir indicate that at higher discharges the bowl tends to generate a thicker warm water layer, possibly due to a rotational or submerged vortex-like effect. Consequently, considerable warming of releases occurs with higher flows even though the intake is nearly 100 feet below the reservoir surface.

A 100-foot-deep, 2,400-foot-long, surface-suspended curtain, which encloses the Spring Creek Power Plant intake, was installed in the spring of 1993. Like the Lewiston flexible reservoir curtain, the Spring Creek intake curtain is designed to retain the warm surface water while allowing only withdrawal of only colder water from lower in the reservoir. Owing to the fact that the intake curtain is very large, a physical model study was not practical. The

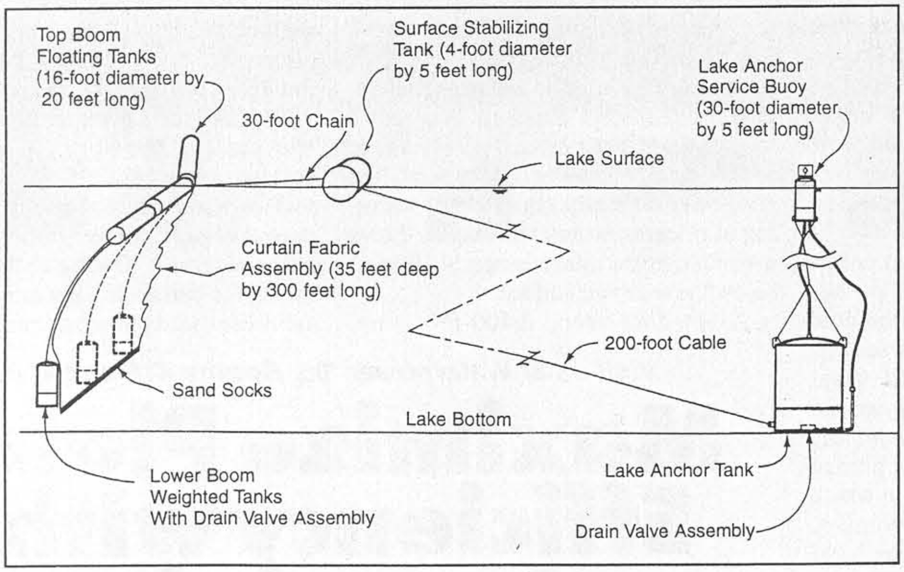

Figure 2: Bureau of Reclamation engineers designed flexible reservoir curtains to manage water temperature in withdrawals from the Lewiston Reservoir in California. As shown in this figure, the curtain fabric is suspended between a top boom of floating tanks and a lower boom of weighted tanks. The curtain assembly is connected by chain to stabilizing tanks that float on the surface. The stabilizing tank, in turn, is connected by cable to an anchor buoy and tank assembly.

mixing zone. For the reservoir and discharge conditions observed in the physical model, the reservoir curtain could reduce temperatures of water diverted to the Clear Creek Tunnel by an average of 2.5 degrees Fahrenheit.

In a range of operational discharges of 1,000 to 3,700 cfs, the testing showed that two curtains in combination would be most effective in controlling the temperature of water released from the reservoir. A curtain at the Clear Creek Tunnel intake could supply temperature control at low-water discharges, and a reservoir curtain could provide temperature control at higher water discharges.

Because actual curtain performance was still unknown, Reclamation began the Lewiston program by designing just the reservoir curtain for the more commonly used higher discharge levels. During the design stage for the reservoir curtain, officials with the California Department of Fish and Game asked Reclamation to design a curtain for the Lewiston Reservoir Fish Hatchery intake, which is near the proposed location for the Clear Creek Tunnel Intake curtain. The fish hatchery intake curtain provides optimum temperature control of water released to the hatchery.

Installing Flexible Curtain

In the summer of 1992, crews installed curtains based on the model research at Lewiston Reservoir. First, crews installed the reservoir curtain used to cool all summer releases, and then they installed an adjustable hatchery intake curtain that cools water released to the fish hatchery.[4] The 830-foot-long, 35-foot-deep reservoir curtain is suspended from tanks on the surface and is held in place by a cable and anchor system. Figure 2 illustrates the configuration of the curtain components in the reservoir.

Because the fish hatchery needed both warm and cool water depending on seasonal conditions, Reclamation designers conceptualized a special hatchery intake curtain. The entire 300-foot-long, 45-foot-deep intake curtain can be submerged by partially filling the surface tanks that hold the curtain in place with water. The submerged curtain becomes a dam that blocks cool water while permitting warm water to be withdrawn over the top. When cooler water is needed, operators raise the hatchery intake curtain to a floating (vertical) position by using compressed air to empty water from the flotation tanks. Total time for engineering, procurement, and construction of both Lewiston Reservoir curtains was five months. The smaller curtain was completely assembled and installed in seven working days. Costs totaled $650,000 for the reservoir curtain and $150,000 for the hatchery curtain.

Evaluating the Effectiveness

To evaluate the effectiveness of the Lewiston Reservoir curtains, personnel from Reclamation, the U.S. Fish and Wildlife Service, and the California Department of Fish and Game cooperated in a temperature-monitoring program. Temperature profiles were measured upstream and downstream from the reservoir curtain site for pre- and post-curtain conditions. As expected, the pre-curtain profiles are essentially identical for upstream and downstream temperatures, but the post-curtain profiles indicate a substantial modification to the reservoir temperature stratification.

These profiles are valid for peaking power operations but are not valid for the typical baseload operations. In that case, the water temperature between the power plant and the curtain should be even more homogenous because warm water cannot accumulate as it would during non-power-generating periods.

Analysis of data collected near the Clear Creek Tunnel Intake that supplies water to Carr Power Plant showed the effectiveness of the reservoir curtain in reducing the temperature of water entering the intake. The average temperature of water released through Carr power plant was reduced by 1 to 2.5 degrees Fahrenheit. The results are based on similar operational conditions such as flow, duration, and time of day. The temperature reduction corresponds well to the reservoir and discharge temperatures observed in the physical model, where the reservoir curtain reduced the temperature of water released through the Clear Creek Tunnel by about 2.5 degrees Fahrenheit. Though 1 to 2.5 degrees Fahrenheit may appear small, Sacramento River temperatures were approaching critical levels in 1992. These slightly lower temperatures helped sustain viable spawning and rearing habitat for threatened salmon populations. But even lower water temperatures were needed. Therefore, Reclamation engineers designed two more curtains for installation at Whiskeytown Reservoir, where colder water predominates.

Modifying Whiskeytown Reservoir

The Whiskeytown Reservoir, which holds 214,000 acre-feet of water and has a maximum depth of 250 feet, is on Clear Creek, a tributary of the Sacramento River. Throughout the summer season, diverted inflows dominate with typical maximum discharge of 3,000 cfs. The diverted inflows are cold, and withdrawals are made from deep in the reser-

Spring Creek intake curtain was fabricated and installed over a four-month period at a cost of $1.8 million.

Although an extensive monitoring system was installed at Whiskeytown Reservoir, operators collected very little performance data in 1993, a wet year. Only limited, intermittent diversions were made through the Carr hydropower plant into Whiskeytown Reservoir during the spring and early summer. Intermittent inflows from Lewiston Reservoir along with withdrawal of cold water from Whiskeytown Reservoir resulted in late summer water at the Spring Creek conduit intake being too warm for release to the Sacramento River. As a consequence, continuous, extended diversions did not occur in 1993. However, the 1994 diversions reflect normal operations, and engineers will analyze the comprehensive data which has been collected.

Looking Forward

Reservoir curtains provide a cost-effective, innovative technology. As a result of Reclamation engineers' theoretical analyses of temperature stratification dynamics, physical model studies, and careful design, four curtains are functioning effectively in two Central Valley Project reservoirs. The reservoir curtains were installed in the most timely way possible.

Preliminary data indicate that the temperature of water released from the Bureau of Reclamation's Spring Creek power plant were 3 to 5 degrees cooler after installation of the reservoir curtains than in prior years with similar operating conditions. Water temperature also was lowered in the Trinity river where salmon populations are threatened. Because water temperature is so important for survival of salmon in the Sacramento River, Reclamation engineers now are constructing a traditional structural withdrawal device at Shasta Dam to lower temperature of water released from the reservoir. And, other design engineers can look toward these flexible-fabric, reservoir curtains as cost-effective solutions to similar problems. ■

Notes:

[1] Bohan, J.P., and J.L. Grace, *Mechanics of Flow from Stratified Reservoirs in the Interest of Water Quality,* Waterways Experiment Station, Technical Report H-69-10, Reclamation, 1969.

[2] Hino, M., Discussion at the Second International Symposium on Stratified Flows, Trondheim, Norway, June 1980.

[3] Smith, D.R., S.C. Wilhelms, J.P. Holland, M.S. Dortch, and J.E. Davis, *Improved Description of Selective Withdrawal Through Point Sinks,* Technical Report E-87-2, U.S. Army Corps of Engineers Waterways Experiment Station, 1987.

[4] O'Haver, G., "Temperature Control Curtains - Lewiston Lake and Hatchery," Presentation at the Power O&M Workshop, U.S. Bureau of Reclamation, Mid-Pacific Region, 1992.

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