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DEVELOPMENT AND USE OF NEW ROUTINES IN CE-QUAL-W2 TO BLEND WATER FROM MULTIPLE RESERVOIR OUTLETS TO MEET DOWNSTREAM TEMPERATURE TARGETS

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Abstract CE-QUAL-W2 is a two-dimensional (longitudinal, vertical) flow and water-quality model developed by the U.S. Army Corps of Engineers. In this work, version 3.12 of CE-QUAL-W2 was modified to enable it to automatically blend water from multiple reservoir outlets and to select optimum depths for sliding-gate (adjustable-elevation) outlets to meet downstream temperature targets. Previous applications of CE-QUAL-W2 were forced to make such operational adjustments outside of the model in an iterative manner, a process that typically required many model runs. These tasks now can be accomplished in a single model run because the necessary operational adjustments are done internally. The model user specifies a time series of target downstream temperatures; the number, type, and characteristics of each outlet; and a time series of reservoir discharge rates. The model then determines which outlets to use, where in the water column to locate any adjustable-elevation outlets, and how much of the released water to take from each outlet.

These changes were tested in an application of CE-QUAL-W2 to a proposed 40-foot raise of Scoggins Dam in northwestern Oregon. Downstream temperature targets were generated by smoothing measured temperatures upstream of the reservoir. Various combinations of fixed- and adjustable-elevation outlets were tested. Results showed that downstream temperature criteria could be met, though the reservoir sometimes ran out of cold water in the fall. The outlet combinations that were best able to meet downstream temperature targets were those that accessed both cold water near the bottom of the lake and warm water near the surface. The greatest operational flexibility typically was provided by adjustable-elevation outlets because they could be moved to access cold or warm water, as necessary. These tests demonstrated the utility of the model modifications, which worked well and saved the model user considerable time.

INTRODUCTION

Large dams can greatly alter the downstream hydrology and water quality of a river. Peak and low flows are modified. Sediment sources are reduced. Daily and seasonal temperature patterns are changed. These and other factors combine to alter the stream's morphology and ecology, thus forcing changes in the use of that resource by resident or migrating aquatic species (Collier et al., 1996). Although dams can be valuable for flood control, power generation, and as storage for agricultural and municipal water supplies, their ecological effects are increasingly being studied, not only to better understand those effects, but to aid in their mitigation. Indeed, many projects have been launched in recent years to quantify the effects of dams on downstream temperatures and to minimize those influences through structural or operational modifications.

Many tall dams release water from only one or two outlets, often to maximize power generation. In reservoirs that experience strong thermal stratification, the deeper outlets typically access cold, dense water while the upper outlets access warmer water. Temperatures downstream from a dam using a relatively deep outlet often are colder in summer and warmer in fall than those that would occur in the absence of the dam. A typical example of this phenomenon is illustrated in figure 1 using data from above and below Henry Hagg Lake, the reservoir formed by Scoggins Dam in northwestern Oregon.

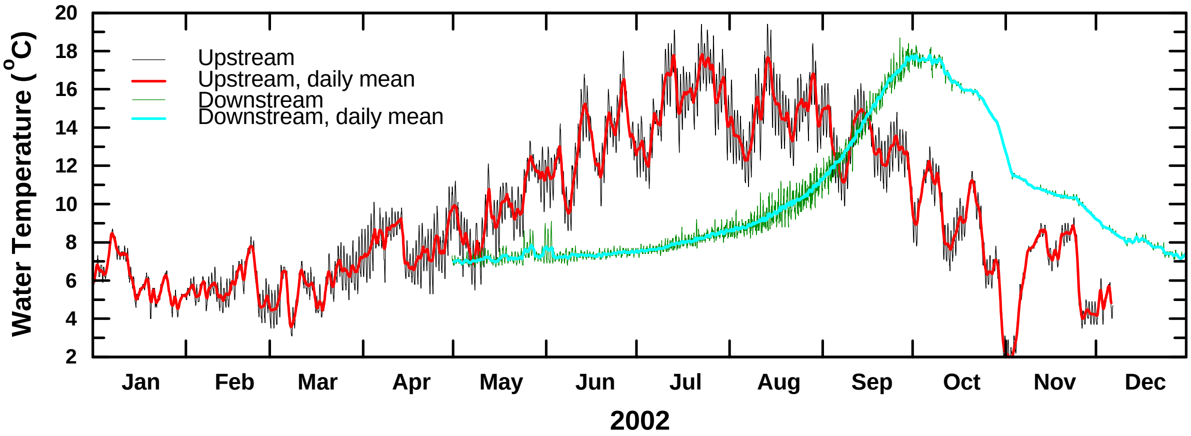

Figure 1. Measured water temperatures in Scoggins Creek upstream and downstream of Henry Hagg Lake in northwestern Oregon, showing the seasonal lag in maximum temperature downstream of the dam caused by the release of water from deep within the lake.

This shift in the seasonal temperature pattern, as well as the dampening of daily and weekly temperature patterns, is common downstream of relatively deep reservoirs and has important ecological consequences. The timing and success of fish migration, spawning and rearing, as well as the type and abundance of resident species, can be affected by such seasonal temperature shifts. To minimize these ecological effects, some dams have been retrofitted with selective withdrawal devices that allow water to be taken and blended from different depths, thus providing some control over the temperature of the discharged water.

For example, the withdrawal structure at Cougar Dam on the South Fork McKenzie River in western Oregon recently was retrofitted by the U.S. Army Corps of Engineers so that water could be withdrawn from multiple selected depths to provide a more natural seasonal temperature pattern downstream from the project. A selective withdrawal structure also was attached to the back face of Shasta Dam in northern California in the mid-1990s, specifically to address downstream temperature effects on fish habitat (Bartholow et al., 2001).

Prior to making such structural changes, an appropriate model typically is used to assess the likely changes to temperature both in the lake and downstream, thus providing feedback for the project's feasibility and design. CE-QUAL-W2, one of the most powerful and often-used reservoir water-quality models, is an appropriate tool for such an analysis, but it was not originally designed to efficiently evaluate these types of operational and structural modifications. In this study, enhancements were made to CE-QUAL-W2 to enable and test such a capability.

METHODS

Model and Modifications CE-QUAL-W2 is a two-dimensional (longitudinal, vertical) water-quality model developed by the U.S. Army Corps of Engineers. W2, as it is commonly called, simulates lake circulation, stage, vertical and horizontal velocities, water temperature, and a host of water-quality constituents including nutrients, algae, dissolved oxygen, and suspended sediment. To simulate water temperature, W2 requires bathymetric and meteorological data, inflow rates and temperatures, the location and release rate of all withdrawals, and various parameters such as light extinction coefficients. W2 has been applied to hundreds of reservoirs all over the world and is capable of simulating water temperatures to a typical accuracy of 0.5-1.0 degrees Celsius (Cole and Wells, 2002).

Although W2 is a powerful tool and can simulate reservoir discharges from multiple outlets, it was not designed to automatically blend water from a subset of those outlets or select optimum depths for sliding-gate (adjustable-elevation) outlets to meet user-specified downstream temperature targets. Previous applications of W2 were forced to make these types of operational adjustments outside of the model in an iterative manner, a process often requiring many model runs (Hanna et al., 1999).

In this work, a new subroutine was added to version 3.12 of W2 which enabled it to blend withdrawals from multiple outlets (choosing two optimum outlets if more are available), and to set the depth of sliding-gate (adjustable-elevation) outlets, in order to meet a user-specified time series of target downstream temperatures. The model user provides the target temperature time series, the type and location of all available outlets for blending, and a time series of reservoir discharges. The user also specifies how often and at what time of day any operator-assisted blending changes can be made. The model and its new subroutine then determine which outlets to use, where in the water column to dynamically locate any adjustable-elevation outlets, and how much water to withdraw from each outlet to best meet the downstream temperature targets.

Study Area and Test Case These code enhancements were tested on an application of W2 to Henry Hagg Lake in northwestern Oregon (figure 2). Hagg Lake was formed behind Scoggins Dam, a 151-foot high earth-fill project built by the Bureau of Reclamation and completed in 1975. The lake itself is 120 feet deep and impounds 62,216 acre-feet of stored water at full pool. It is used for flood control, downstream flow augmentation, recreation, and as a source of agricultural, municipal, and industrial water for the nearby population. Though the dam has a spillway to accommodate the release of high flows, it is only rarely used. Most releases are made through a single lake outlet located approximately 70 feet below the lake's full-pool elevation. The lake is deep enough that it undergoes thermal stratification early in the spring and retains that thermal structure until late fall. The outlet typically resides in the lake's hypolimnion in the summer, though releases for downstream water users usually lowers the thermocline to the elevation of the outlet by early fall (Sullivan and Rounds, 2005).

To meet projected future water demands, the height of Scoggins Dam may be increased by as much as 40 feet, resulting in a rough doubling of the lake's storage. If such a project were undertaken, however, the modified dam might be required to include a selective withdrawal tower that could blend warm water from near the lake's surface with cold water from near the bottom to provide a more natural seasonal temperature pattern downstream, thus mitigating the seasonal temperature lag shown in figure 1.

A W2 model of Hagg Lake recently was constructed and calibrated by Sullivan and Rounds (2005) and provides an excellent test case for these new code modifications. Several outlet combinations were evaluated with the model in combination with a 40-foot dam raise:

A. The lake's existing fixed-elevation outlet only
B. Two fixed-elevation outlets (the existing outlet and a new outlet located at the current full-pool elevation, which would be 40-feet deep at full pool with the dam raise)
C. One adjustable-elevation outlet, similar to a simple single-opening sliding gate assembly
D. One adjustable-elevation outlet, paired with the lake's existing fixed-elevation outlet

Two water-use scenarios were evaluated, simulating low (minimum) and high (maximum) levels of future municipal water demand, which result in different water levels in the lake at the end of the dry summer season.

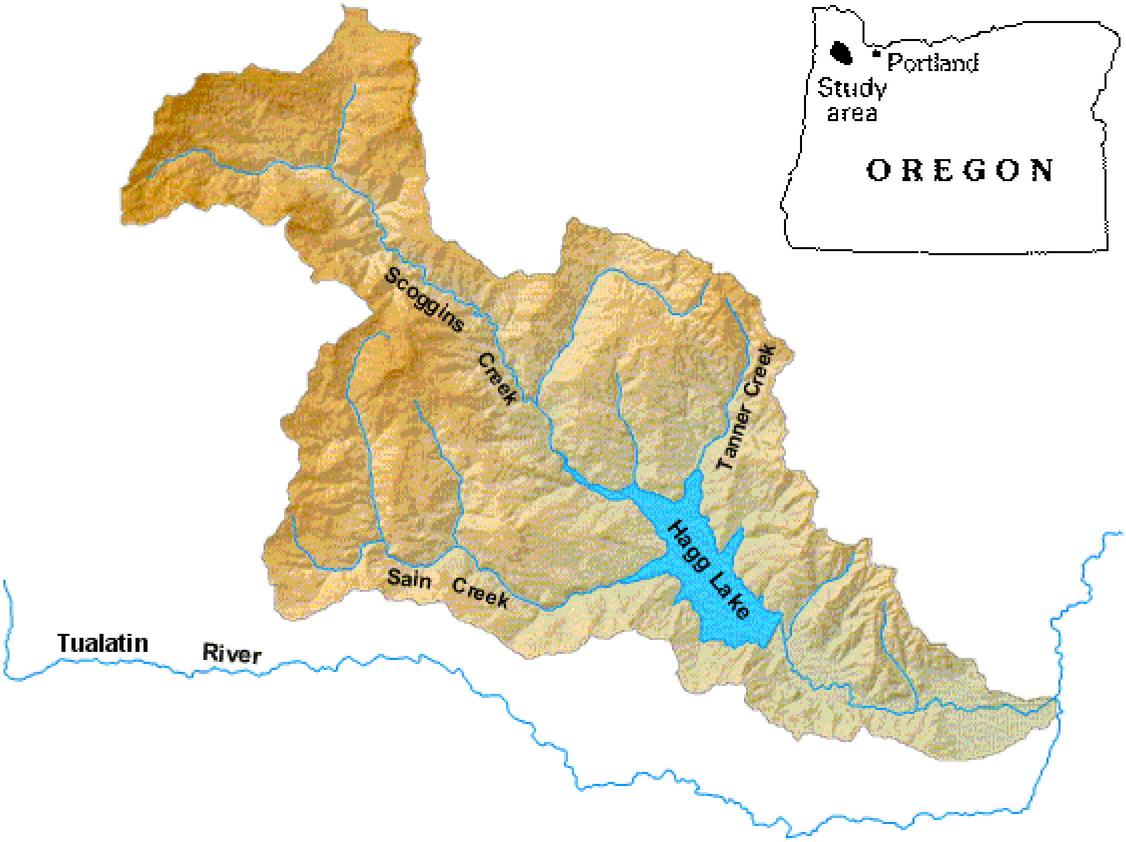

Figure 2. Shaded relief map of the Scoggins Creek drainage in northwestern Oregon, showing the location of Henry Hagg Lake, formed by Scoggins Dam.

Finally, a downstream target temperature time series was constructed to determine whether all of the heating effects of the reservoir could be avoided. To that end, measured daily maximum temperatures from 2002 in Scoggins Creek upstream of the reservoir were smoothed to remove the signals of that year's weather patterns. The resulting smoothed data (the green line in figure 3) were used as the target temperatures for Scoggins Creek downstream of the project. Other criteria for downstream target temperatures could be developed and tested as well, but this target served as a good test for the model's capabilities.

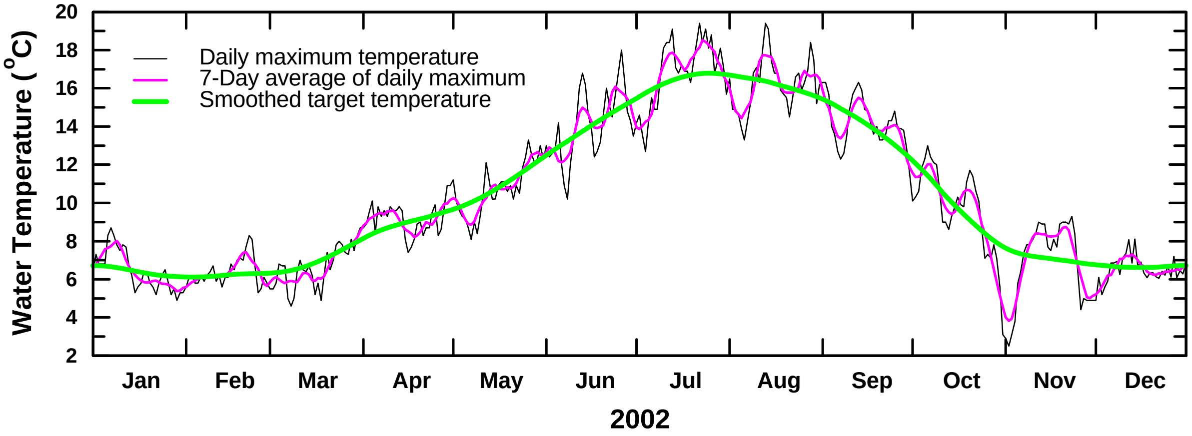

Figure 3. Construction of a downstream temperature target from measured daily temperature maxima upstream of the reservoir. The 7-day average is used in Oregon's temperature standard. The influence of weather patterns was removed via smoothing with 30-day running averages.

RESULTS AND DISCUSSION

Each of the model scenarios was run with the modified W2 code, although the new code was not required for scenario A, the one using only the existing fixed-elevation lake outlet. In that case, no blending from multiple or adjustable-elevation outlets was possible and the downstream target temperatures were ignored by the model. The relative success of each scenario was evaluated based on its ability to (a) match the downstream temperature target and (b) avoid exceedances of a maximum temperature standard in the water released from the dam. Oregon's maximum temperature standard for Scoggins Creek downstream of Hagg Lake is 13 degrees Celsius from mid-October through mid-May and 18 degrees Celsius in the balance of the year to protect fish spawning and rearing uses, respectively.

Results from all four scenarios are shown in figure 4. As expected, the released temperatures from scenario A have a pattern that is similar to those that were measured in 2002 (figure 1). Neither water-use pattern in scenario A results in a seasonal temperature pattern that resembles the target. Only by keeping the lake relatively full and keeping the outlet well below the thermocline can downstream temperature violations be avoided, as in the low-demand water-use model run. Larger releases, as in the high-demand water-use run, brought the lake's stored summer heat (near the surface) down to the level of the outlet and caused that heat to be discharged downstream late in the year when it could be a problem for fish spawning.

In scenario B (two fixed-elevation outlets), the temperature blending was straightforward. The model was told how much water to release, and the temperatures at the elevations of the two outlets in the lake were known because they were calculated by the model; therefore, finding the optimum flow into each outlet to match the temperature target was a simple computation. If the target could not be matched exactly, then all of the release was taken from the outlet whose temperature was closest to the target. Figure 4B shows that the target could not be achieved

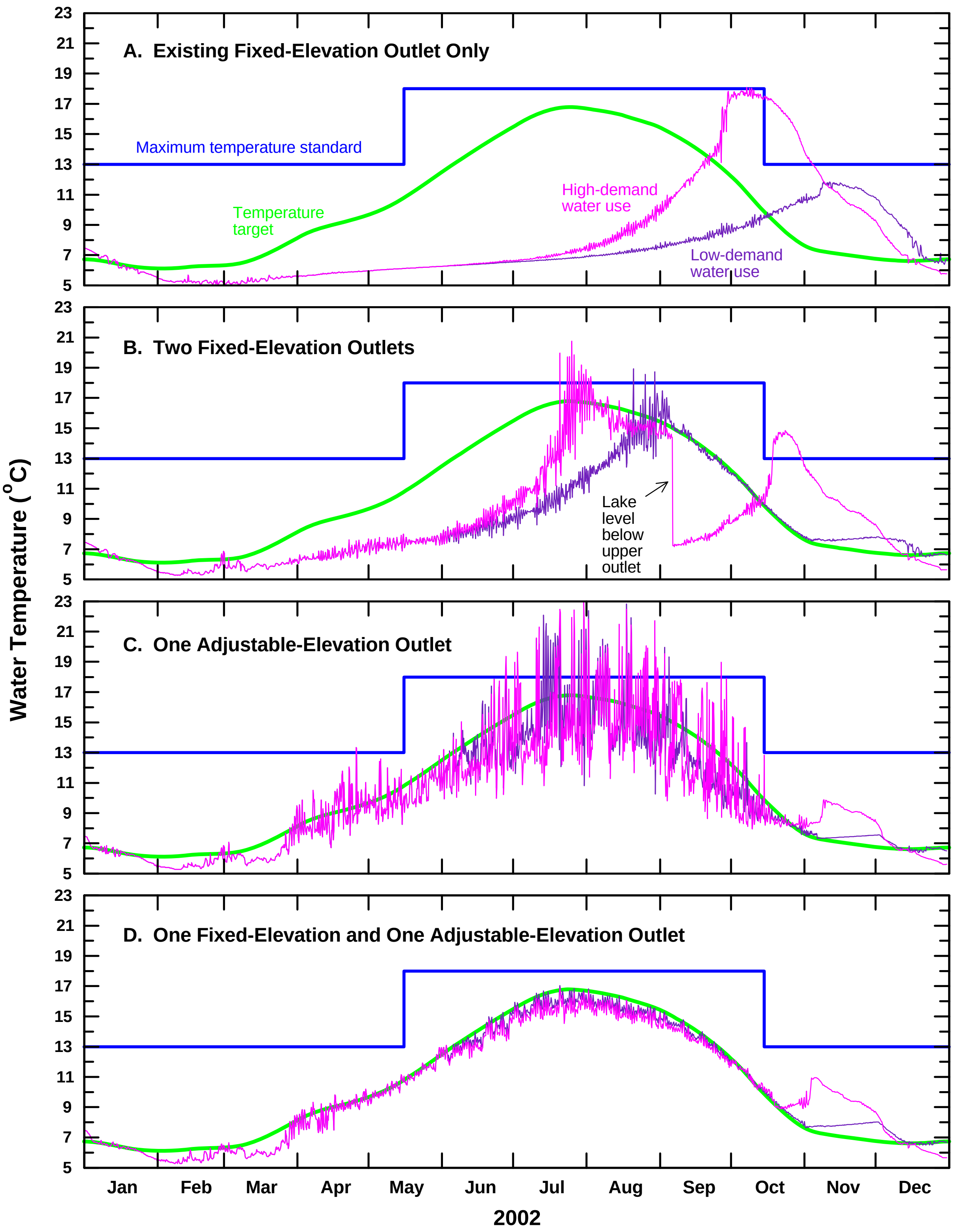

Figure 4. Results of blending scenarios using different types of reservoir outlets, demonstrating that only certain combinations of outlets can match the downstream temperature target and be in compliance with Oregon's maximum temperature standard for the reach downstream of the dam. The two water-use scenarios have different release schedules, resulting in different lake levels.

early in the summer; this was because both fixed outlets were too deep to access the warm water at the lake's surface. For those periods when the target was bracketed by the temperatures at the two outlets, successful blending could be carried out. In the high-demand water-use run, however, the lake level dropped below the elevation of the upper outlet in early September, effectively ending all blending possibilities for the year and causing large deviations from the target temperatures.

Scenario C used only one adjustable-elevation outlet. For the sake of simplicity, it was assumed that only one opening could be produced, though it could be placed at almost any depth, from the elevation of the original fixed-elevation outlet to about 5 feet below the water surface. Figure 4C shows that the seasonal pattern in the downstream temperature target could be matched using only one adjustable-elevation outlet; however, the daily variation in the temperature of the released water was large and sufficient to cause potential violations of the maximum temperature standard. The use of only one adjustable-elevation outlet forced the model to position that outlet in the lake's thermocline during periods of stratification because the target temperature was between the temperatures of the lake's epilimnion and hypolimnion. Underwater waves (seiches) produced by surface winds cause the thermocline to rise and fall in the course of a day, thus delivering water of different temperatures to the outlet, which in these runs was repositioned by the model only once a day. Clearly, adjustable-elevation outlets are useful, but their utility is diminished when they must be positioned in the lake's thermocline.

Finally, scenario D combined the lake's original fixed-elevation outlet with an adjustable-elevation outlet. During most of the year, the fixed-elevation outlet had access to water that was colder than the target temperature. Accordingly, the model positioned the adjustable-elevation outlet near the lake's surface to access water that was warmer than the temperature target. By bracketing the target temperature in this way, effective blending was achieved (figure 4D). Note that the released water had less daily variation in temperature than that in scenario C, due to the fact that the warm and cold water sources were less affected by any internal seiching of the lake. Scenario D was able to match the downstream target temperature fairly well throughout the year, except in late October and November when the lake no longer had any water that was cold enough to match the downstream target. Still, no violations of the maximum temperature standard occurred, and the downstream reach was restored to a fairly natural seasonal temperature pattern.

EVALUATION OF CODE MODIFICATIONS

In all of the tested scenarios, the model's new subroutine performed as expected and demonstrated its utility. Assuming that achieving downstream temperature targets is the top priority for dam operation (the overall release rate is a given), the new subroutine effectively anticipates the necessary operational modifications in the course of a single model run with no additional input required of the model user. All operational adjustments are done internally, thus removing the need for additional runs to refine the placement of adjustable-elevation outlets, reassess the choice of outlets, or modify the fraction of water released from any one outlet. With these code enhancements, the model may be used to determine whether downstream temperature targets can be met under various structural and operational scenarios, and assess the effectiveness of different combinations of outlets.

Results from the test case showed that temperature criteria downstream of Scoggins Dam could be met, though the lake might run out of cold water in the fall under a high-demand water-use scenario. The outlet combinations that were best able to meet downstream temperature targets were those that accessed both cold water near the bottom of the lake and warm water near the surface. The greatest operational flexibility typically was provided by adjustable-elevation outlets such as sliding gates, because they could be moved to access cold or warm water, as necessary. These tests demonstrated the utility of the model modifications, which worked well and allowed the effectiveness of the test scenarios to be evaluated quickly and efficiently.

These model modifications have been submitted to the Corps of Engineers team that oversees the development of the W2 model. The code used with the Hagg Lake test application is or soon will be available from the USGS project website at http://or.water.usgs.gov/tualatin/hagg_lake/.

REFERENCES

Bartholow, J., Hanna, R.B., Saito, L., Lieberman, D., Horn, M. (2001). “Simulated limnological effects of the Shasta Lake temperature control device,” Environmental Management, 27(4), pp 609-626.

Cole, T.M., Wells, S.A. (2002). “CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.1,” U.S. Army Corps of Engineers Instruction Report EL-02-1 [variously paged].

Collier, M., Webb, R.H., Schmidt, J.C. (1996). “Dams and rivers: A primer on the downstream effects of dams,” U.S. Geological Survey Circular 1126, 94 p.

Hanna, R.B., Saito, L., Bartholow, J.M., Sandelin, J. (1999). “Results of simulated temperature control device operations on in-reservoir and discharge water temperatures using CE-QUAL-W2,” Journal of Lake and Reservoir Management, 15(2), pp 87-102.

Sullivan, A.B., Rounds, S.A. (2005). “Modeling hydrodynamics, temperature and water quality in Henry Hagg Lake, Oregon, 2000-2003,” U.S. Geological Survey Scientific Investigations Report 2004-5261, 38 p.