Prepared in cooperation with City of Portland Bureau of Environmental Services

Development of a CE-QUAL-W2 Temperature Model for Crystal Springs Lake, Portland, Oregon

Open-File Report 2016–1076

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of Crystal Springs Lake, Portland, Oregon. Photograph by Adam J. Stonewall, U.S. Geological Survey, July 10, 2014.

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Area	
hectare	2.471	acre
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as:

$$°F=(1.8×°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as:

$$°C=(°F-32)/1.8$$

Datums

Vertical coordinate information is referenced to the City of Portland Vertical Datum (Datum conversion information is available in Portland Bureau of Transportation, 2015).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

7dADM	7-day average of the daily average maximum temperature
BES	Portland Bureau of Environmental Services
COR	Pearson correlation coefficient
DEM	digital elevation model
DO	dissolved oxygen
MAE	mean absolute error
ME	mean error
NS	Nash-Sutcliffe model efficiency
ODEQ	Oregon Department of Environmental Quality
TMDL	total maximum daily load
USGS	U.S. Geological Survey

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Abstract

During summer 2014, lake level, streamflow, and water temperature in and around Crystal Springs Lake in Portland, Oregon, were measured by the U.S. Geological Survey and the City of Portland Bureau of Environmental Services to better understand the effect of the lake on Crystal Springs Creek and Johnson Creek downstream. Johnson Creek is listed as an impaired water body for temperature by the Oregon Department of Environmental Quality (ODEQ), as required by section 303(d) of the Clean Water Act. A temperature total maximum daily load applies to all streams in the Johnson Creek watershed, including Crystal Springs Creek. Summer water temperatures downstream of Crystal Springs Lake and the Golf Pond regularly exceed the ODEQ numeric criterion of 64.4 °F (18.0 °C) for salmonid rearing and migration. To better understand temperature contributions of this system, the U.S. Geological Survey developed two-dimensional hydrodynamic water temperature models of Crystal Springs Lake and the Golf Pond. Model grids were developed to closely resemble the bathymetry of the lake and pond using data from a 2014 survey. The calibrated models simulated surface water elevations to within 0.06 foot (0.02 meter) and outflow water temperature to within 1.08 °F (0.60 °C). Streamflow, water temperature, and lake elevation data collected during summer 2014 supplied the boundary and reference conditions for the model. Measured discrepancies between outflow and inflow from the lake, assumed to be mostly from unknown and diffuse springs under the lake, accounted for about 46 percent of the total inflow to the lake.

Model simulations (scenarios) were run with lower water surface elevations in Crystal Springs Lake and increased shading to the lake to assess the relative effect the lake and pond characteristics have on water temperature. The Golf Pond was unaltered in all scenarios. The models estimated that lower lake elevations would result in cooler water downstream of the Golf Pond and shorter residence times in the lake. Increased shading to the lake would also provide substantial cooling. Most management scenarios resulted in a decrease in 7-day average of daily maximum values by about 2.0–4.7 °F (1.1 –2.6 °C) for outflow from Crystal Springs Lake during the period of interest. Outflows from the Golf Pond showed a net temperature reduction of 0.5–2.7 °F (0.3–1.5 °C) compared to measured values in 2014 because of solar heating and downstream warming in the Golf Pond resulting from mixing with inflow from Reed Lake.

Introduction

Crystal Springs Lake and the small mixing pond downstream (named the "Golf Pond" for this report) are surrounded by the Eastmoreland Golf Course and the Crystal Springs Rhododendron Garden owned by Portland Parks and Recreation (fig. 1). The area supports a diverse and productive biota that includes many species of birds, small mammals, fish, and rooted and floating aquatic vegetation.

The City of Portland Bureau of Environmental Services (BES) has replaced seven culverts in Crystal Springs Creek and restored approximately 5,400 linear feet of riverbank since 2010 to enhance fish passage for threatened salmonids and to reduce temperatures and localized flooding. Two more culverts are scheduled to be replaced in 2016. BES also partnered with the U.S. Army Corp of Engineers and Portland Parks and Recreation to transform a 2.5-acre (about 1.0 hectare) instream pond in Westmoreland Park to a meandering stream. BES seeks to further understand the temperature contributions of open water bodies upstream of these improvements and how the changes relate to downstream conditions to help meet the requirements of Oregon Department of Environmental Quality's (ODEQ) total maximum daily load (TMDL) for temperature in Johnson Creek, of which Crystal Springs Creek is a tributary.

The TMDL stipulates a 7-day average of the daily maximum stream temperature (7dADM) of 64.4 °F (18.0 °C) for Johnson Creek and its tributaries to ensure sufficiently cool water for year-round salmonid survival and a lower criterion of 55.4 °F (13.0 °C) during salmonid spawning season (October 15–May 15). Crystal Springs Creek (USGS streamgage 14211542) exceeded the TMDL by an average of 3.2 °F (1.8 °C) for 42 percent of calendar years 2003–13. Most of the summer streamflow in lower Johnson Creek is from Crystal Springs Creek (see section, "Observed Data Summary and Development of Boundary Conditions" for details).

Replacing culverts in Crystal Springs Creek enhanced aquatic habitat but did not directly address temperature concerns. Crystal Springs Lake and Reed Lake, both of which are upstream of most of the replaced culverts, increase Crystal Springs Creek water temperatures to levels that are detrimental to salmonids, which require cold water refuge in summer.

Purpose and Scope

BES asked the USGS to assist with temperature modeling of Crystal Springs Lake and the Golf Pond to analyze streamflow and temperature effects resulting from various potential lake management strategies, including maintaining current conditions. This report documents the development and calibration of a CE-QUAL-W2 temperature model of Crystal Springs Lake and the Golf Pond. The model can be used to simulate the temperature at various depths and at the outflow from both water bodies. The model also can be configured with potential management options for the lake and (or) pond and can be used to simulate the resulting changes in outflow temperature. Twelve potential management scenarios, including maintaining current conditions, were simulated. Additionally, the hypothetical removal of the dam and Crystal Springs Lake, although not a viable management option, was simulated to estimate the lowest temperature that could be achieved. The CE-QUAL-W2 model was calibrated using data collected in summer 2014.

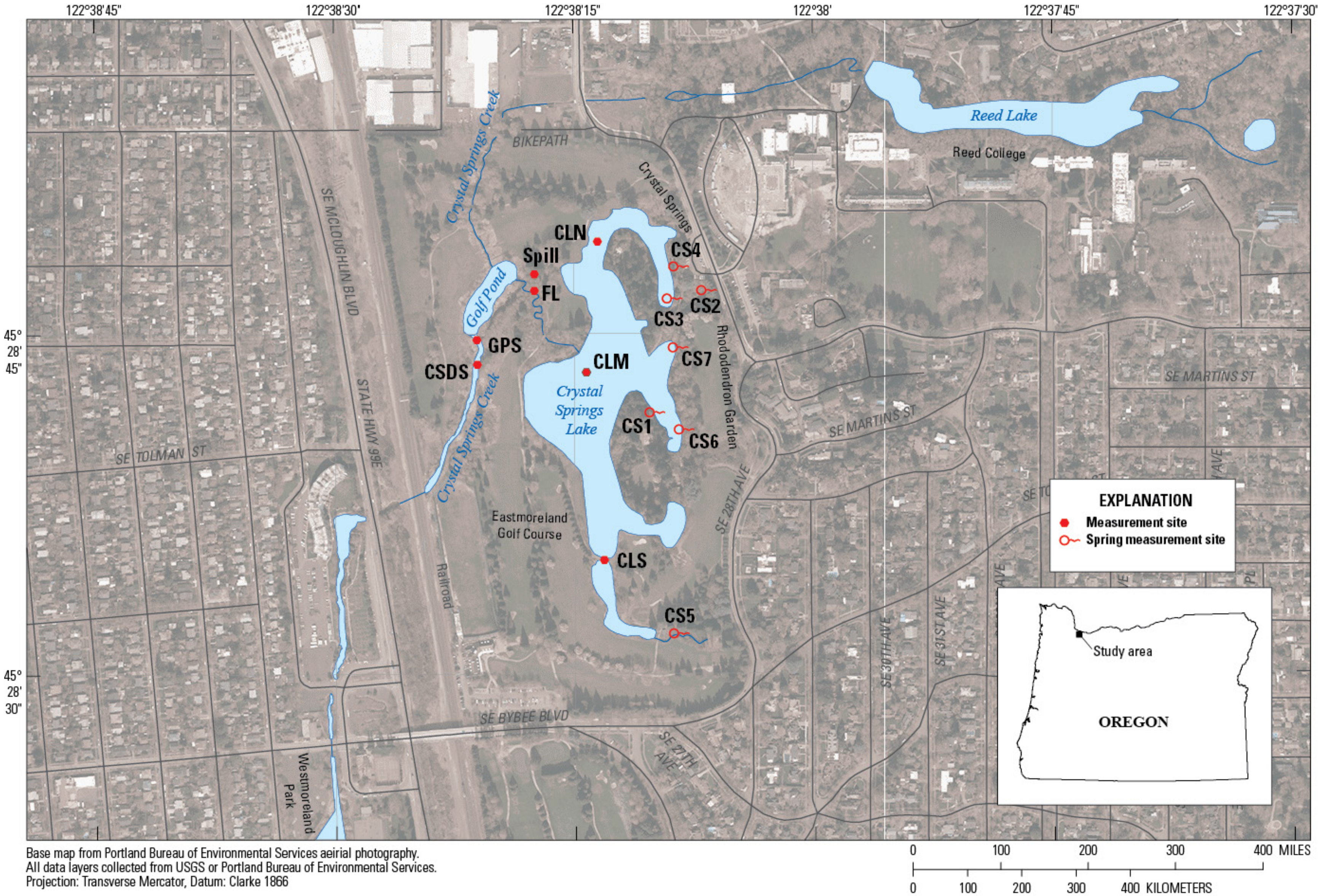

Figure 1. Map showing study sites at Crystal Springs Lake, the Golf Pond, and surrounding area, Portland, Oregon.

Background

Study Area

Crystal Springs Creek and Crystal Springs Lake are located in a heavily urbanized area in southeast Portland, Oregon (fig. 1). The Reed Canyon branch of the creek originates from springs around Reed College campus. Springwater flows into Reed Lake, which is bound by a dam. The creek flows westward through a fish ladder in Reed Canyon, continues west under SE 28th Avenue, then turns south into the Eastmoreland Golf Course. At the golf course, it flows into the Golf Pond, where it mixes with another branch from Crystal Springs Lake. About one-quarter of the streamflow into the Golf Pond is from this Reed Canyon branch of the creek.

Crystal Springs Lake is impounded by a dam on the Eastmoreland Golf Course. The lake is bounded to the northeast by the Crystal Springs Rhododendron Garden and in other directions by the golf course.

Crystal Springs Lake and the Golf Pond have areas of 12.4 acres (5.0 hectares) and 0.74 acres (0.30 hectares), respectively (AKS Engineering, 2014). The Crystal Springs Creek watershed has a temperate, marine climate with warm, dry summers and cool, wet winters. Mean precipitation in the watershed is 43.5 in. (110 cm) (U.S. Geological Survey, 2015). During the months of July, August, and September, precipitation at the airport averages less than 3.5 in. (8.8 cm) (National Oceanic and Atmospheric Administration, 2015a). The effective watershed is significantly smaller than the topographical watershed due to storm water infrastructure. The topographical watershed is 96.6 percent urban (primarily a residential neighborhood and college campus), and about half the area is covered by impervious surfaces.

Crystal Springs Lake is surrounded by tall vegetation in the northeast where it borders the Crystal Springs Rhododendron Garden, and moderate to low vegetation (grass) everywhere else where it borders the golf course. Most of the lake does not get much shading. The exception is the eastern edge of the lake, which borders Crystal Springs Rhododendron Garden. The east side of the Golf Pond is well shaded, whereas the rest of the pond is largely exposed to daytime sunlight.

Crystal Springs Lake is fed primarily by spring flow (Lee and Snyder, 2009) that might include water from springs originating underneath the lake. At least seven springs originate east or south of the lake and flow into the lake as surface water (fig. 2). Water exits the lake over the dam spillway or through the fish ladder to the south, both of which feed into the Golf Pond downstream. A mid-channel gravel bar running north to south in the pond directs flow from the lake spillway to the west side of the Golf Pond, while water from the fish ladder flows mostly into the relatively narrow, shaded channel on the east side of the Golf Pond. However, there does appear to be some interchange between the two outflows before reaching the Golf Pond, with some of the fish ladder outflow entering the spillway channel (see section, “Observed Data Summary and Development of Boundary Conditions-Streamflow”).

The west side of the Golf Pond is also fed by the Reed Canyon arm of Crystal Springs Creek, which flows from Reed Lake upstream. The west side is wider and flow is slower than the east side. The two sides of the Golf Pond join at the southern end of the pond before exiting to re-form Crystal Springs Creek.

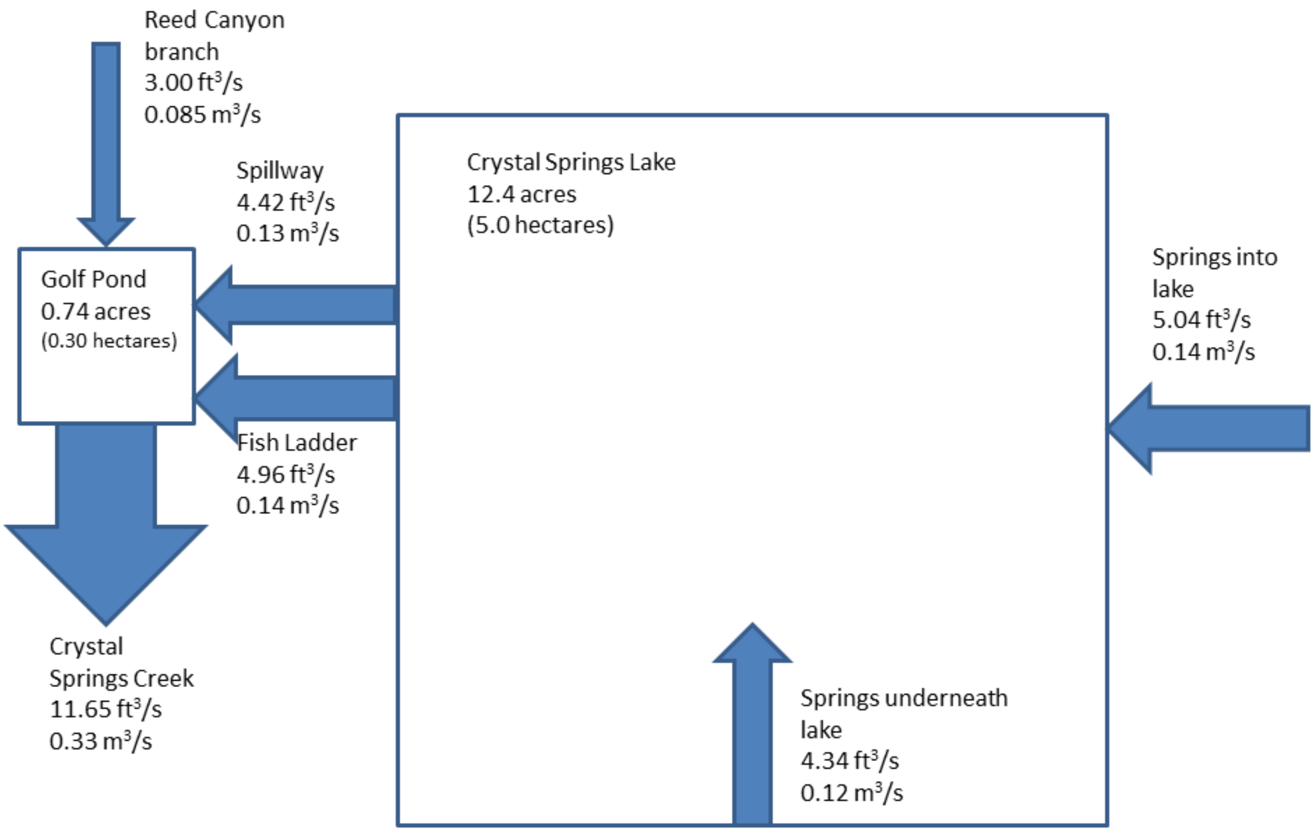

Figure 2. Schematic diagram showing streamflow to and from Crystal Springs Lake, the Golf Pond, and surrounding area, Portland, Oregon.

Methods and Data

Model Description

The Crystal Springs Lake temperature model was created using CE-QUAL-W2, version 3.72, released April 2015 (Cole and Wells, 2015). CE-QUAL-W2 is a two-dimensional, laterally averaged, hydrodynamic water-quality model originally developed by the U.S. Army Corps of Engineers and updated by Portland State University (available from Portland State University, 2015 http://www.ce.pdx.edu/w2/). It has been applied to river, lake, and reservoir systems around the world, including many in Oregon (Sullivan and Rounds, 2006; Sullivan and others, 2007, 2014; Buccola and others, 2013; Rounds and Buccola, 2015). Development and calibration of the Crystal Springs CE-QUAL-W2 temperature model consisted of three steps:

1. Development of lake and pond bathymetry and other geometric data;
2. Compilation or estimation of boundary conditions; and
3. Calibration of streamflow, water elevation, and water temperature measurements.

Development of Bathymetry and Other Geometric Data

A bathymetric survey of Crystal Springs Lake and the Golf Pond was completed in August 2014 by a contractor hired by the City of Portland. A digital elevation model (DEM) of the geometric data was then used to develop the relation between area and volume as a function of water-surface elevations for Crystal Springs Lake and the Golf Pond (figs. 3 and 4). Geospatial data were simplified to construct the model bathymetry. As a result, both the lake surface area and volume represented by the CE-QUAL-W2 grid generally were less than DEM values (mean volumetric error of -1,506 m^3 or percent mean error of -12 percent), especially at lake elevations below 59.1 ft (18.0 m). This discrepancy is not considered to have substantial effects on results, as the ratio of surface area/volume is fairly consistent between the model and DEM. The relations between simulated and measured bathymetry were used as guides in developing separate model grids for the lake and pond that captured physical bathymetric features while maintaining model stability.

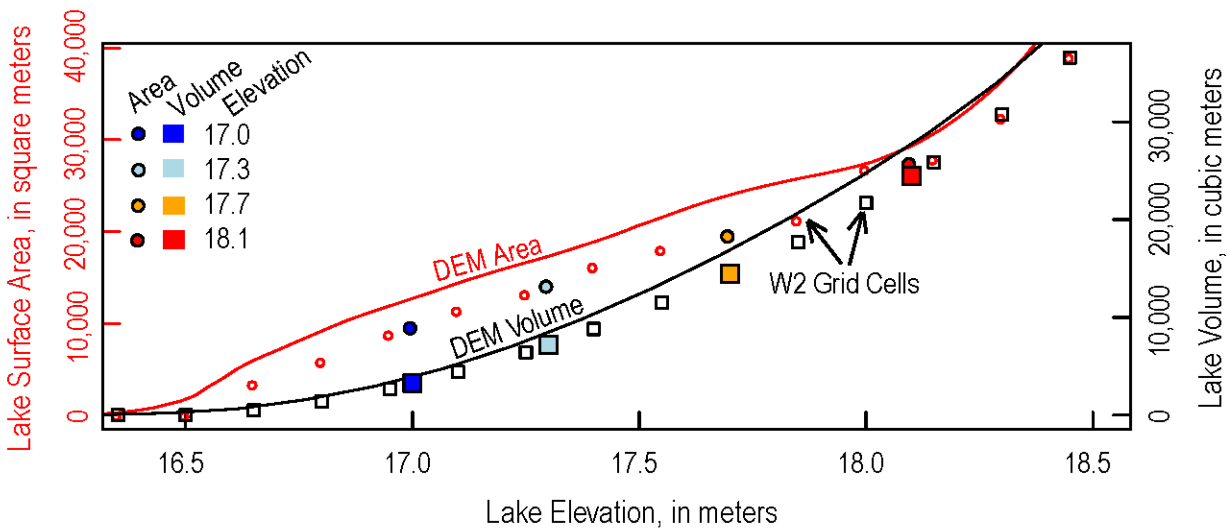

Figure 3. Graph showing comparison of water-surface elevation, lake surface area, and lake volume from CE-QUAL-W2 grid and a digital elevation model (DEM) for Crystal Springs Lake, Portland, Oregon.

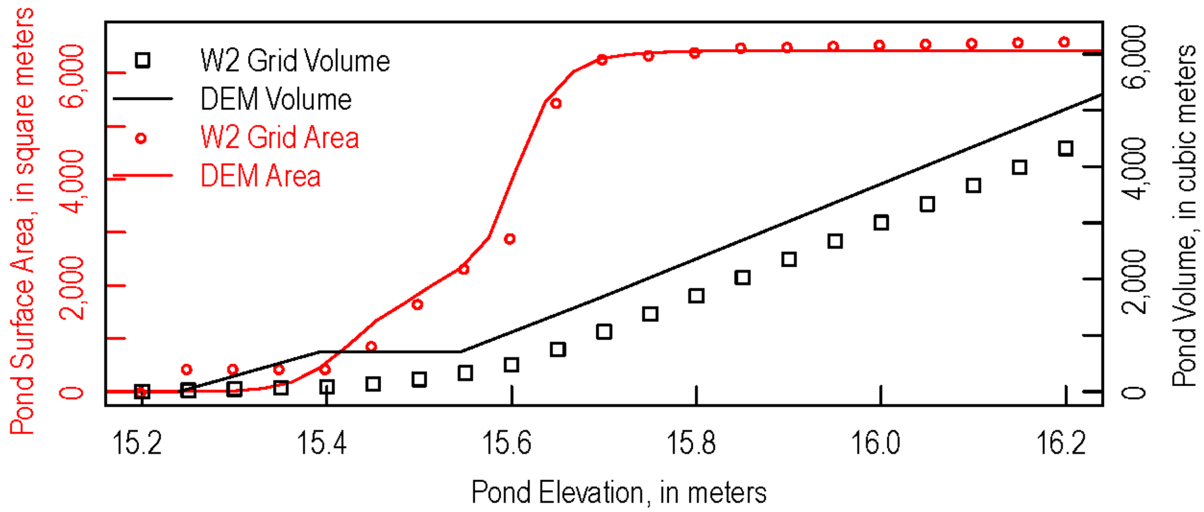

Figure 4. Graph showing comparison of water-surface elevation, surface area, and volume from CE-QUAL-W2 grid and a digital elevation model (DEM) for the Golf Pond, Portland, Oregon.

By creating a model grid that resembled these relations at all elevations, the model could be assumed to be accurate at lower lake elevations that were not observed during the calibration timeframe. The final model grids were comprised of 32 and 6 segments for the lake and pond, respectively (figs. 3 and 4, table 1). Vertical layers were set to heights of 0.49 and 0.16 ft (0.15 and 0.05 m) for the lake and pond, respectively. The lake was spilt into two branches, one flowing from the Crystal Springs Rhododendron Gardens to the north, and the other originating from the golf course in the south (fig. 5). The average number of active layers in the lake model ranged from two (in the shallower northern and southern arms) to eight (near the center of the lake), corresponding to an average cell depth ranging from 1.0 to 5.2 ft (0.30 to 1.60 m). Throughout the simulation period, there were six to eight active layers in the Golf Pond model corresponding to an average cell depth of 1.0–1.3 ft (0.30–0.40 m).

Table 1. Selected CE-QUAL-W2 model parameter values for the Golf Pond, Oregon.
[Table 1 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

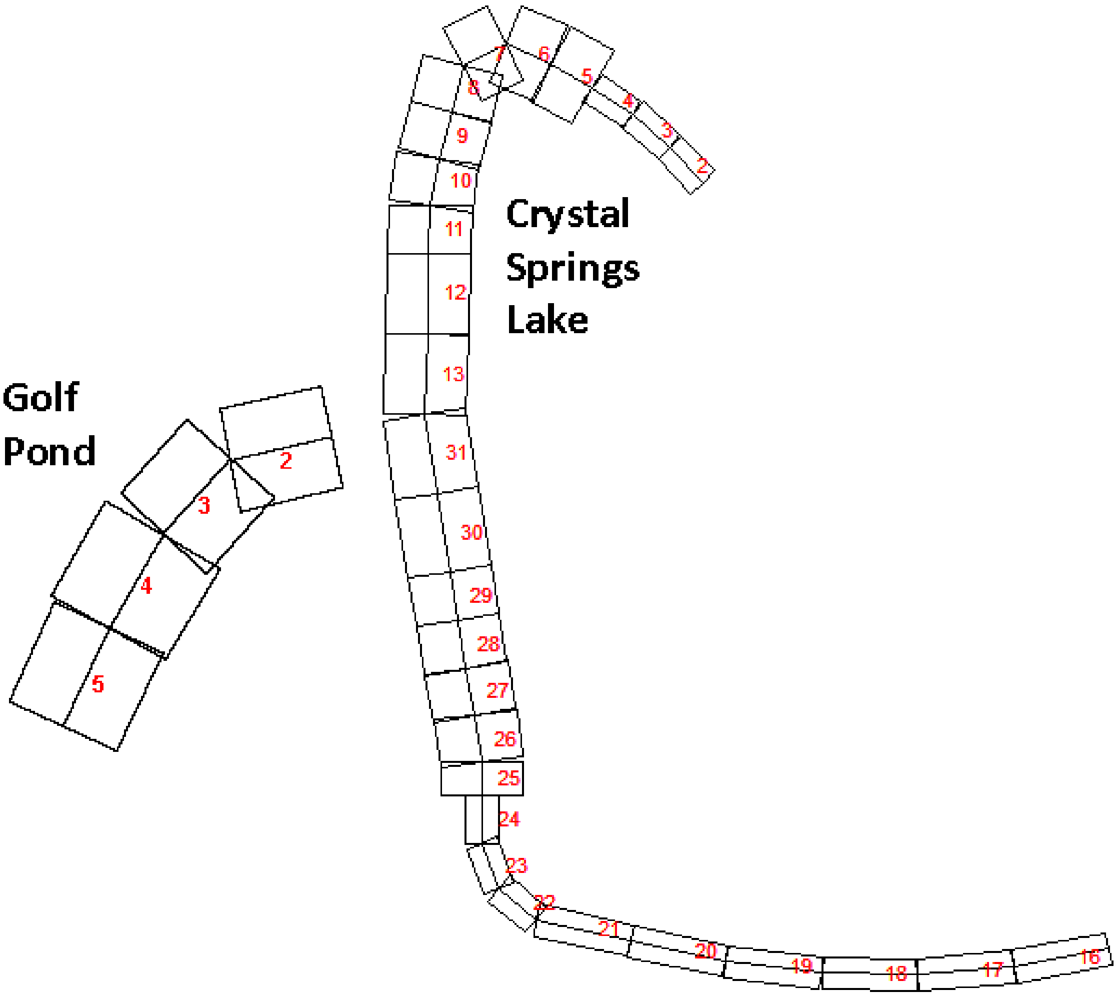

Figure 5. Diagram showing CE-QUAL-W2 model grid of Crystal Springs Lake and the Golf Pond, Portland, Oregon.

Data Summary and Development of Boundary Conditions

Continuous streamflow and (or) temperature data were collected at 15 sites in and around Crystal Springs Lake (table 2). Streamflow measurements of springs were made away from point of issuance in locations where discharge from the springs was similar to typical streams (well-distributed flow confined in a channel). All streamflow measurements and temperature data were collected either by USGS personnel according to USGS protocol (Wagner and others, 2006; Turnipseed and Sauer, 2010) or by BES. When possible, measured data from these sites were used for boundary conditions or as calibration checks to the model output. Other data were estimated either by using regression relations with nearby sites or as detailed later in this section.

Table 2. Monitoring sites near Crystal Springs Lake, Portland, Oregon.
[Table 2 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

Streamflow

Streamflow was measured monthly from May through October 2014 at site CS6, the largest of seven known springs that feed Crystal Springs Lake (table 3 and fig. 1). Streamflow ranged from 1.71 to 2.46 ft^3/s (0.048 to 0.070 m^3/s), and did not exhibit a temporal trend. Daily streamflow was estimated by linear interpolation between measurements dates.

Table 3. Streamflow measurements from springs and inflow and outflow points of Crystal Springs Lake and the Golf Pond, Portland, Oregon.
[Table 3 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

The other six springs that discharge to Crystal Springs Lake (sites CS1, CS2, CS3, CS4, CS5, and CS7) were measured one to three times between July and October 2014 (table 3 and fig. 1). Streamflow measurements at these six sites ranged from 0.1 ft^3/s (0.003 m^3/s) to 0.85 ft^3/s (0.024 m^3/s). Streamflow measurements from these six springs are less accurate than those from site CS6 and from Crystal Springs Creek due to non-ideal measurement conditions (for example, low streamflow rates and shallow depths). Typical uncertainties in the measurement of spring streamflow were estimated at ± 0.2 ft^3/s (0.006 m^3/s). Although this uncertainty is large relative to the streamflow of these six springs (0.1–0.85 ft^3/s, or 0.003–0.24 m^3/s), it is small relative to the overall outflow from the lake (typically between 9 and 10 ft^3/s, or 0.25 and 0.28 m^3/s). Streamflow from these six springs was assumed to be the same and assumed to be constant for the modeling period, and the mean of all streamflow measurements from these six springs was used. The springs are unresponsive to precipitation events, as evidenced by the lack of temperature fluctuations after precipitation events. For the study period, average weekly precipitation was 0.12 in. (0.30 cm), and the maximum weekly precipitation (September 18–24, 2014) was 0.86 in. (2.18 cm) (U.S. Climate Data, 2015). Maximum daily precipitation was on September 24 (0.58 in. or 1.47 cm).

Streamflow at the two lake outflows, the dam spillway, and the fish ladder (sites Spill and FL in table 3 and fig. 1), was also measured at least monthly from May through October 2014. The spillway and fish ladder outflows enter the Golf Pond in close proximity. Streamflow measurements made along the length of both outflows (August 5, 2014) indicated that there was interchange between the two outflows, resulting in a net movement of water from the fish ladder outflow to the spillway outflow. Consequently, it was decided to use only measurements made near the downstream end of the spillway and fish ladder outflows. Daily streamflow at each site was estimated by linear interpolation between measurements. Outflows from the lake were defined as two separate withdrawals (one located at the end of each branch of the model), with parameters shown in table 1.

Streamflow from Crystal Springs Creek at SE 28th Avenue (site 28th; table 3 and fig. 1) and upstream of the railroad crossing (site CSDS; table 3 and fig. 1) was measured at least monthly between May and October 2014. Streamflow varied little at both sites, with standard deviations of 0.38 and 0.71 ft^3/s (0.011 and 0.02 m^3/s), respectively. Daily streamflow at both sites was estimated by linear interpolation between measurements.

In late summer, streamflow from Crystal Springs Creek typically constitutes more than one-half of the streamflow of Johnson Creek. For example, for August 2014, the average streamflow at USGS streamgage 14211550, located between the confluence with Crystal Springs and the mouth of Johnson Creek, was 16.7 ft^3/s (0.47 m^3/s) (U.S. Geological Survey, 2015), whereas average streamflow measurements made downstream of the Golf Pond were 11.7 ft^3/s (0.33 m^3/s) (table 3).

Lake and Pond Elevation

The water-surface elevation was continuously measured near the middle of Crystal Springs Lake (site CLM) and at the south end of the Golf Pond (site GPS) using submersible pressure transducers throughout the study period. These data were converted to City of Portland Datum (1.375 ft [0.419 m] above NGVD 29 and 2.10 ft [0.640 m] below NAVD 88) based on the difference to surveyed benchmarks near the lake shore (AKS Engineering, 2014; City of Portland, 2015). Lake water-surface elevations ranged between 59.12 ft (18.02 m) and 59.78 ft (18.22 m), whereas the Golf Pond water-surface elevations ranged between 50.59 ft (15.42 m) and 51.35 ft (15.65 m). Based on data from the bathymetric survey and spot points of depth measured during instrument deployment, maximum depths of the lake and pond were 8 ft (2.4 m) and 3 ft (0.9 m), respectively.

Temperature

Eighteen continuous (recorded every 15 or 30 minutes) temperature probes were installed at 13 locations (table 4), including two probes each at different depths at GPS and CS5 and four probes at different depths at CLM. When possible, probes were placed at well-mixed sections at inflows and outflows and temperature probes were placed in spring inflows to Crystal Springs Lake at close proximity to the lake rather than close to the spring source. The length of the record among sites varied considerably due to installation by different agencies (USGS and BES), deployment of additional probes after the initial data assessment, and technical issues with individual probes.

Table 4. Location of continuous temperature probes and summary of measurements, Crystal Springs Lake, Portland, Oregon.

[Table 4 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

Water temperatures of the springs flowing into Crystal Springs Lake varied little over the deployment period, especially at springs in close proximity to the lake. For example, the upper probe at CS5 varied from a minimum of 56.1 °F (13.4 °C) to a maximum of 56.5 °F (13.6 °C) between August 5 and October 9, 2014. The variation in average daily temperature at the four springs that were measured continuously (CS2, CS5, CS6, and CS7) ranged from 0.1 to 1.2 °F (0.04 to 0.7 °C). Springs with greater daily temperature ranges had longer distances between the spring headwaters and the lake (for example, CS2 and CS7). Because of the relatively small diurnal variation in temperature at the monitored springs, the daily water temperatures at other springs without continuous water temperature probes (sites CS1, CS3 and CS4) were estimated by interpolating between discrete field measurements. Estimated daily water temperatures at sites CS3 and CS4 varied from 55.0 to 55.2 °F (12.8 to 12.9 °C). Estimated daily water temperatures at site CS1 varied from 55.2 to 55.9 °F (12.9 to 13.3 °C).

The variations in water temperature in the lake were substantially greater than the variations in the inflowing springs due to exposure to direct sunlight, large surface area, and relatively long residence time of water in the lake. Prevailing northern winds typically moved warm surface water from the north arm and mid-lake to the south arm of the lake. The prevailing wind and the shallow water in the southern arm of the lake (site CLS) resulted in a greater diel range in temperatures at that site than at the north-lake site (site CLN). At mid-lake (site CLM), water temperature and diel range in water temperature decreased with depth. Consequently, because the most shallow temperature probe at mid-lake (site CLM) was considerably deeper (1.6 ft [0.49 m]) than at CLS or CLN, the mean diel temperatures are not directly comparable. The lowest-elevation probe at CLM (depth of 6.6 ft) was presumed to have been buried in sediment and was not used for this analysis.

During July and August 2014, the flow-weighted average outflow temperature from the lake (labeled as “Spill and FL Mix 7dADM” in figure 6) was about (5–16 °F) 3–9 °C warmer than the temperature of springs flowing into the lake (labeled as “Upstream Mix” in figure 6). During early May and late October, the weighted average 7dADM lake outflow temperature exceeded the ODEQ TMDL criterion of 55.4 °F (13.0 °C) for salmonid spawning season (October 15–May 15) in listed tributaries of the Johnson Creek watershed (Oregon Department of Environmental Quality, 2006). Below the pond (site CSDS), 7dADM temperatures in July and August 2014 were within “sub-lethal limits” for cold-water fish species (as described in Oregon Department of Environmental Quality, 2006, table 5.9) and exceeded the ODEQ TMDL criterion for salmonid rearing and migration (64.4 °F [18 °C] in listed tributaries in the Johnson Creek watershed (Oregon Department of Environmental Quality, 2006).

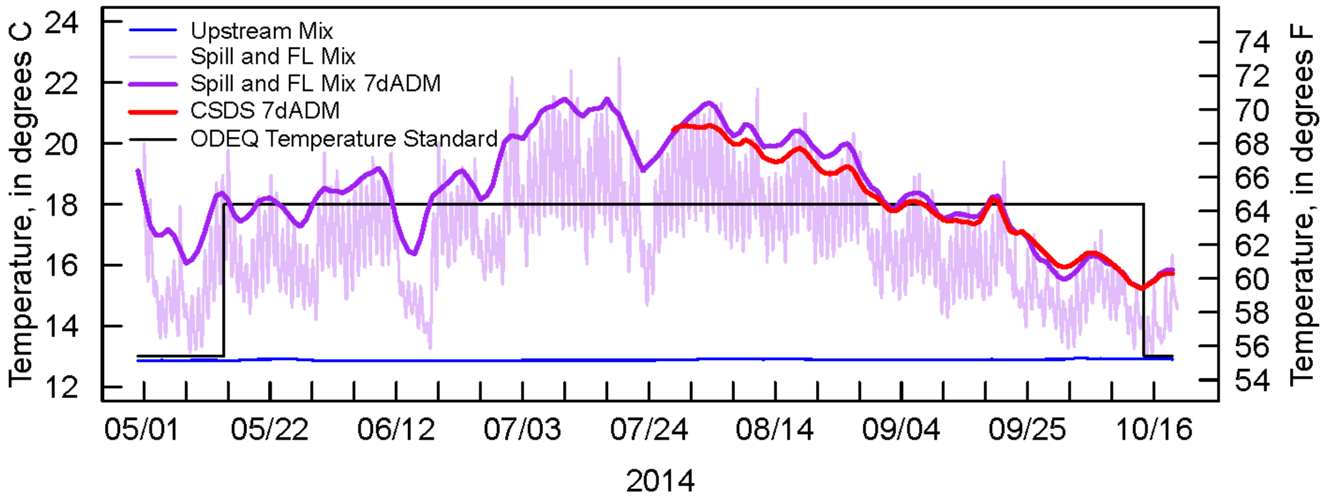

Figure 6. Graph showing measured summer inflow ("Upstream Mix") and outflow ("Spill and FL Mix") water temperatures at Crystal Springs Lake, Oregon. Spill data were used as a surrogate for FL data 09-29–10-20 due to sensor fouling. Abbreviations: 7dADM, 7-day average of daily maximum; ODEQ, Oregon Department of Environmental Quality; CSDS, site downstream of the Golf Pond.

Water temperatures measured at the outflow of the west side of the Golf Pond (site GPS) were about 1°C warmer than those measured in the east side (site GPEA) (table 4). One of the likely reasons for this is the more extensive tree-canopy shading on the east side of the pond compared to the west side of the pond. The average daily temperatures of water flowing into the west side of the pond from sites 28th and Spill are both cooler (62.0° and 62.1 °F, respectively, or 16.7 °C) than the fish ladder (site FL, 63.0 °F or 17.2 °C) that feeds the east side. During warmer weather in August–October, daily maximum water temperatures of outflows from the Golf Pond typically were lower than the inflowing water from Crystal Springs Lake, suggesting that Reed Lake outflows (as measured at site 28th) provided a relative cooling effect as it mixed with Crystal Springs Lake outflow through the Golf Pond during the summer 2014 monitoring period (fig. 6).

Meteorological Data

Water temperature simulations using CE-QUAL-W2 required time series of air temperature, dewpoint temperature, wind speed and direction, solar radiation, and cloud cover. Hourly time series of solar radiation were obtained from USGS site 452359122454500 in Tigard, Oregon (U.S. Geological Survey, 2015). Daily time series of air temperature, dewpoint temperature, wind speed and direction, and cloud cover were obtained from the National Oceanographic and Atmospheric Administration site located at Portland International Airport (station GHCND:USW00024229 [National Oceanic and Atmospheric Administration, 2015b]) and interpolated to hourly timesteps to match the solar radiation data.

Model Calibration

Water Balance

Prior to calibrating for temperature, the simulated CE-QUAL-W2 lake-surface elevations were harmonized with measured lake elevations to assure that simulations included equivalent volumes of water and lake-surface area as recorded. Lake temperature simulations can be sensitive to lake levels, especially in relatively shallow systems such as Crystal Springs Lake and the Golf Pond. As the model grid was adjusted to match the relations defined by the DEM between lake elevation, surface area, and volume (figs. 3 and 4), the water balance was affected. Model stability and grid resolution were also factors in the grid development and re-assessed with the water balance after each iteration of the model grid.

Measured inflow to Crystal Springs Lake was about 54 percent of the total outflow, not accounting for evapotranspiration. The difference is assumed to be due to groundwater discharge through the lake bed and was accounted for in the model using a distributed tributary (QDT). After an initial model run with QDT values of the difference between measured outflow and inflow to the lake, the QDT was developed iteratively as follows:

1. Compute the differences between simulated and measured lake water surface elevation and volume and convert to a time-series of volumetric flow, using the volume-elevation curves for the lake (fig. 7A).
2. Assign the time series of volumetric flow from step 1 to the QDT and re-run the model.
3. Repeat steps 1 and 2 until a satisfactory match between simulated and measured lake water-surface elevation is achieved.

The lake QDT was calibrated to a temperature of 57.2 °F (14 °C, about the same temperature as many of the springs flowing into the lake) and ranged between 26 and 52 percent of the total measured lake inflow. The total QDT was divided in half and placed at model segments 2 (at the head of branch 1, at the north arm of the lake) and 30 (near the location of site CLM). QDT placement/location was also part of the model calibration.

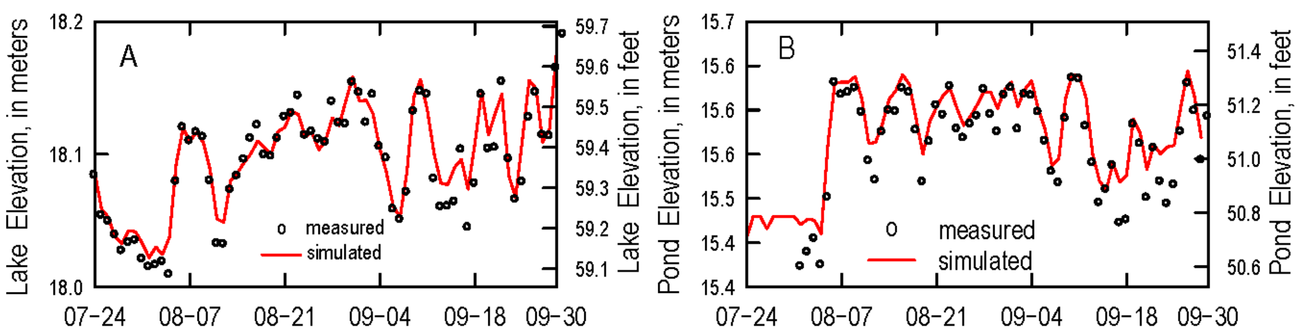

Figure 7. Graphs showing measured and simulated water surface elevation of (A) Crystal Springs Lake and (B) the Golf Pond, Portland, Oregon.

The Golf Pond QDT was developed using the same method as the lake, but with the volume-elevation curve representing the pond (fig. 4) used to convert daily lake elevation differences to volumetric flow. The Golf Pond QDT values ranged between -1 and 6 percent of total pond inflow and were assigned the same temperature as those measured downstream of the lake spillway outflow (site Spill). This optimization process of developing the QDT inflow boundary conditions led to calibrated water-surface elevations within 0.03 and 0.07 ft (0.01 and 0.02 m) mean absolute error (MAE) for the lake and pond respectively (table 5; fig. 7).

Table 5. Calibration fit statistics for sites at Crystal Springs Lake and the Golf Pond, Portland, Oregon.
[Table 5 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

Temperature

Following water balance calibration, the simulated water temperatures were checked against measured water temperatures in the lake, downstream of the lake, in the pond, and downstream of the pond. Simulated lake water temperature was compared to measurements at CLN, CLS, CLM, Spill, and FL as adjustments to the model grid and parameters governing the boundary conditions were made. The factors that had the most effect on water temperature in the lake were the temperature and placement of the QDT inflow boundary conditions within the model grid. Although the quantities of the unmeasured inflowing springs were deduced through the water balance procedure, the locations of these springs were unknown. The model was used to help locate the potential location of the springs (QDT) as it best represented the measured temperature data with the final location that was selected (described in section, “Water Balance”). Shade cover and wind sheltering were also tested. Although no quantitative shade data were available from the lake, a rudimentary analysis assuming 10–15 m of 100 percent effective shade on the east side of the lake showed minimal shading effect on the amount of solar radiation reaching Crystal Springs Lake, especially at mid-day when solar intensity is greatest. Consequently, the shade and wind parameters were set to the default values of 1 (no shade cover and no adjustment to wind speed) for each segment in the lake grid. Shade values of 0.5–0.8 were used for the calibrated the Golf Pond model.

A combination of figures 8–11 and goodness-of-fit statistics (table 5) were used to assess the performance of the lake and pond models. The north and south arms of the lake (sites CLN and CLS, respectively; figures 8 and 9A) were well matched by the simulations, aside from some under-estimation of the daily peak temperature. Lake outflow temperatures at sites FL and Spill matched well with measured values (figs. 9B–C), resulting in MAE values of 0.60°C and 0.57°C, respectively. Due to malfunctioning probes, fewer data were available near the middle of the lake at site CLM to validate the simulations (fig. 10). Overall, temperatures were better matched near the surface (site CLM 1.6) than at depth (sites CLM 3.0 and CLM 3.9). Nevertheless, the general pattern and magnitudes are correctly simulated.

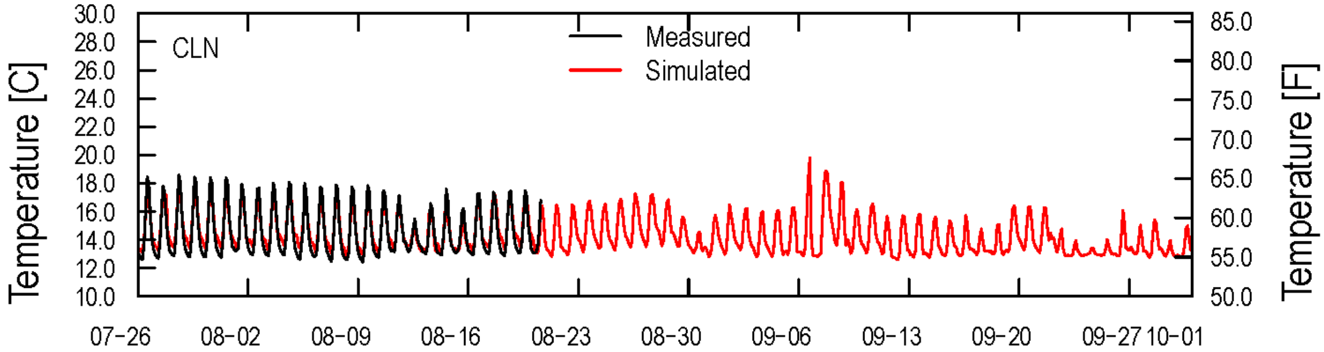

Figure 8. Graph showing comparison of measured and simulated water temperature at site Crystal Springs Lake North (CLN), Crystal Springs Lake, Portland, Oregon.

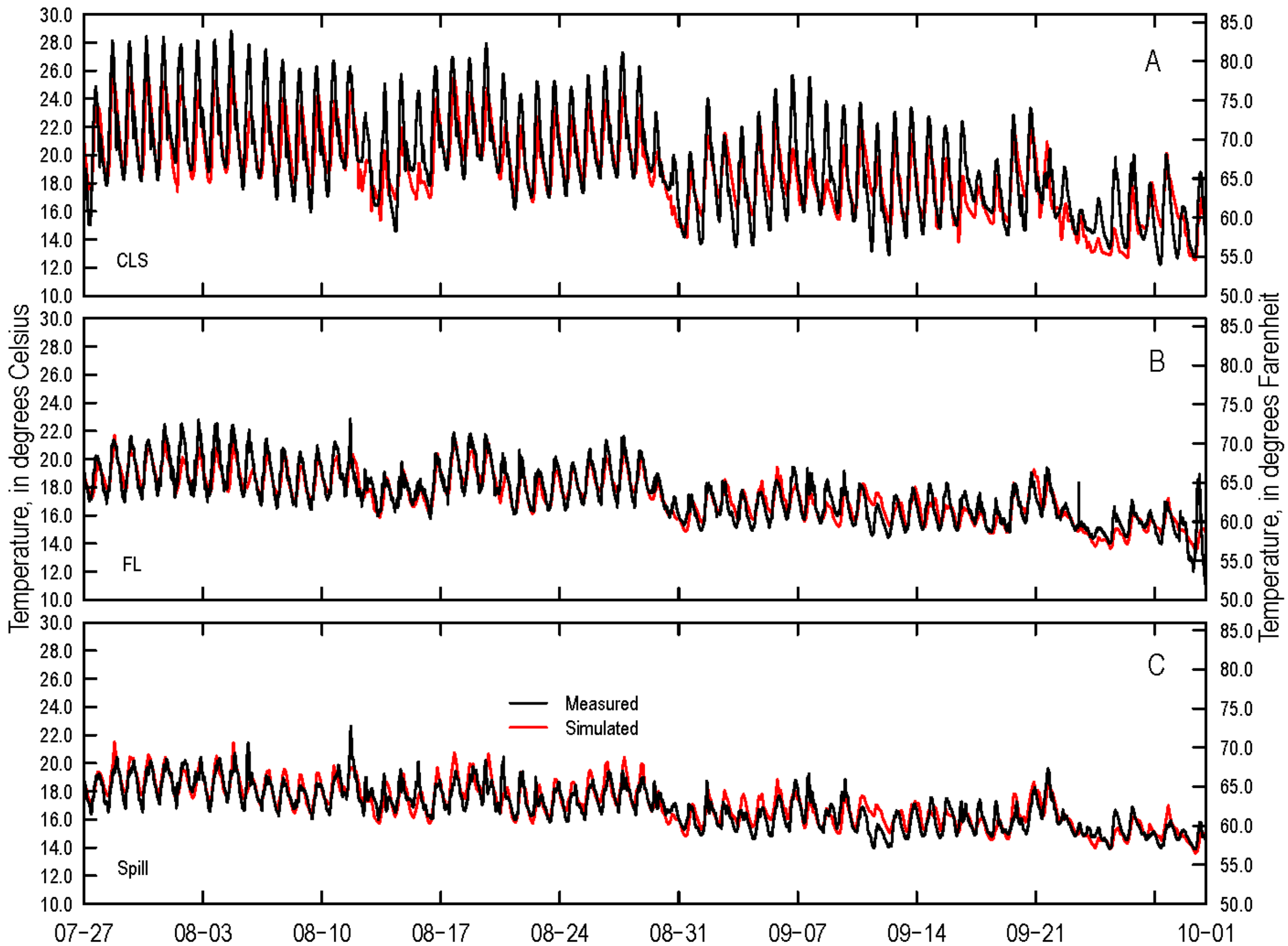

Figure 9. Graphs showing comparison of measured and simulated water temperature at sites (A) Crystal Springs Lake South (CLS), (B) fish ladder outflow (FL), and (C) spillway outflow (Spill), Crystal Springs Lake, Oregon.

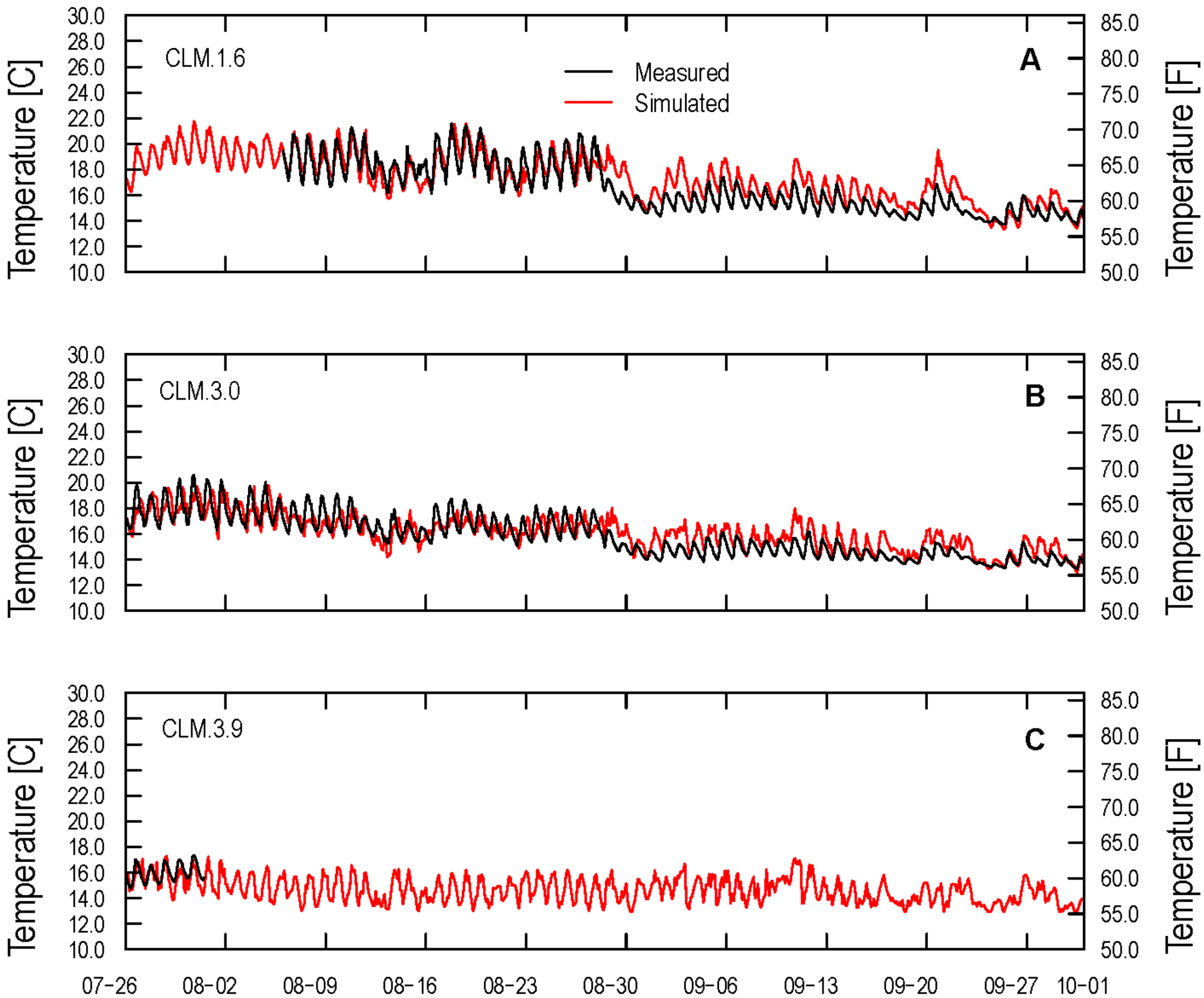

Figure 10. Graphs showing comparison of measured and simulated water temperature at sites (A) Crystal Springs Lake Middle (depth = 1.6 ft; CLM.1.6); (B) Crystal Springs Lake Middle (depth = 3.0 ft; CLM.3.0); (C) Crystal Springs Lake Middle (depth = 3.9 ft; CLM.3.9).

Overall, simulated the Golf Pond water temperatures closely matched measured values (fig. 11; table 5) with MAE values of 0.44°C in the southwestern corner of the pond (site GPS) and 0.28°C at the outflow of the pond (site CSDS). Some overestimates of daily maxima and underestimates of minima were observed during August and could be related to extreme heat during that time. This relatively small discrepancy was localized to the west side of the pond and could be attributed to solar radiation, boundary conditions, or assumptions related to bed-sediment heat exchange in CE-QUAL-W2.

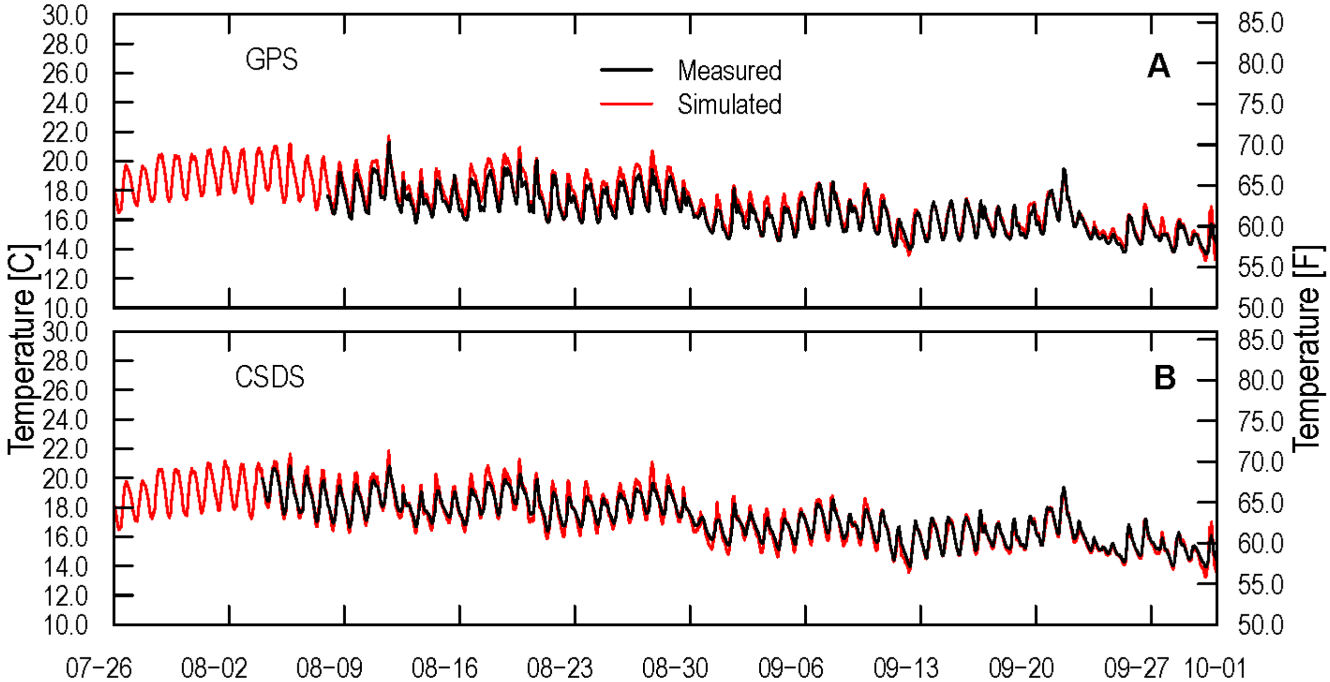

Figure 11. Graphs showing comparison of measured and simulated temperature at sites (A) east arm of the Golf Pond (GPS) and (B) Crystal Springs Creek above railroad (CSDS), Crystal Springs Lake, Portland, Oregon.

Scenarios

Scenario Setup

To evaluate the feasibility of reducing the temperature of the water downstream of the Golf Pond through lake management, 12 management scenarios were evaluated (table 6). Lake water-surface elevations of 55.8 ft (18.1 m) (average of 2014 conditions), 59.4, 58.1, 56.8, and 55.8 ft. (17.7, 17.3, and 17.0 m) were evaluated. Because little variation in water-surface elevation was observed during summer 2014, a constant elevation was used in scenarios evaluating lower levels.

Model stability became problematic at elevations below 55.8 ft (17.0 m). Water-surface elevation in the Golf Pond was unaltered in all scenarios. Discharge to and from the lake were also unaltered. Scenarios involving lower lake levels assume the elevation of the fish ladder entrance would be lowered to a level that would maintain the same proportion of streamflow between the spillway and the fish ladder; unaltered, the fish ladder would be dry at lake elevations less than 59.1 ft (18.0 m). However, because the temperatures of the fish ladder and spillway sites are relatively close, it was surmised that if the fish ladder was allowed to go dry it would not have a dramatic effect on the overall model simulation results. Consequently, all streamflow out of the lake was routed through the spillway for model scenarios with lake water-surface elevations below 59.1 ft (18.0 m).

Table 6. List of management scenarios evaluated for Crystal Springs Lake, Portland, Oregon.
[Table 6 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

In addition to the four simulated lake levels, the effect of hypothetically having no dam (removal of the lake) was also investigated (*UpstreamMix* in table 6). The *UpstreamMix* is meant to illustrate the lowest possible scenario for outflow temperatures and allows an examination of the mixing influence of Reed Lake outflow and the amount of heating that occurs in the Golf Pond. If the *UpstreamMix* scenario was set to show a negligible effect on downstream temperatures, it would not have been necessary to evaluate other potential improvement scenarios.

Because the model was unstable at lake water-surface elevations below 55.8 ft (17.0 m), the flow-weighted average inflow temperature to Crystal Springs Lake was used as the upstream boundary temperature to the Golf Pond model under the *UpstreamMix* scenario. Lake outflow was then run through the Golf Pond model, the same configuration as that applied to the calibrated lake and pond model system. The *UpstreamMix* scenario does not include warming between the spring inflow and lake outflow. If warming were to have been applied for distance traveled, the warming likely would have been less than about 0.50 °F (0.28 °C), based on a maximum summer warming rate (1.0 °F/mi or 0.35 °C/km) documented by Rounds (2010) applied for 0.5 mi (0.8 km) (maximum travel distance from inflowing springs to the dam).

The other variable evaluated through scenarios was shading of Crystal Springs Lake. Although some mature tree canopy currently exists along the northern arm and some inlets of the lake, much of this area was not included in the model because of relatively shallow depths. For this reason, a static shade value of 0 was designated for the calibrated lake model, whereas the calibrated pond model included effective shade shading levels between 20 and 80 percent. Effective shade represents the percentage of solar radiation that is not absorbed by the water (blocked by shade). CE-QUAL-W2 includes a feature termed dynamic shading. Dynamic shading takes into account model latitude, sun position, and the size, position, and effectiveness of the lakeside vegetation to calculate solar radiation input. For the dynamic shading of the lake, vegetation was assumed to be mature (average height of 32.8 ft or 10 m) and an average of 3.28 ft (1 m) from the lake boundary. Two levels of effective shade were considered, heavy shade (80 percent effective shade) and light shade (20 percent effective shade). Shading of the Golf Pond was unaltered.

Scenario Temperature Results

Lowering the water-surface elevation in Crystal Springs Lake resulted in increased area to volume ratios and in a large reduction in the residence time of water in the lake (table 7). A lake elevation of 17.7 m (0.4 m lower than 2014 levels) resulted in a residence time of approximately 0.5 day, compared to 1.1 days of residence time in 2014 (lake elevation about 18.1 m). The lowest water level evaluated (17.0 m) resulted in a residence time of 0.1 day. Reductions in the lake residence time resulted in cooler outflows, as water passes from its origin at one of the springs to the outflows at either the spillway or fish ladder with less time to absorb solar radiation in the lake (tables 8 and 9). By comparison, residence time in the pond is short, less than 1 hour.

Table 7. Average residence times for Crystal Springs Lake and the Golf Pond, Portland, Oregon.
[Table 7 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

Table 8. Comparison of weekly 7-day average of the daily average maximum temperature (7dADM) flow-weighted average temperatures at the outflow from Crystal Springs Lake for the simulation period in 2014 under each scenario, Portland, Oregon.
[Table 8 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

Table 9. Comparison of weekly 7-day average of the daily average maximum temperatures (7dADM) at the outflow from the Golf Pond for the simulation period in 2014 under each scenario, Portland, Oregon.
[Table 9 is a Microsoft© Excel file and can be downloaded at http://dx.doi.org/10.3133/ofr20161076.]

Simulated 7dADM outflow temperatures from Crystal Spring Lake and the Golf Pond under 2014 conditions of shading are shown in figures 12A (lake) and 12B–D (pond). In contrast to the 2014 (current conditions) model, all management scenarios were warmer downstream of the Golf Pond than immediately downstream of Crystal Springs Lake (tables 8 and 9). This is a result of the relative difference between the average daily air temperature and the stream temperature (heat diffusion). A higher temperature gradient between the atmosphere and the water allows for more heat to transfer from the former to the latter. As a result, scenarios resulting in the coolest 7dADM lake outflow temperatures also had the highest increase in 7dADM temperature between lake and pond outflows.

Simulated 7dADM outflow temperatures generally decreased as the lake level decreased. The temperature decrease was larger in August than in September. Scenarios with the greatest decrease in mean 7dADM compared to 2014 conditions had lower lake levels and higher effective shade (*MeanDifFrom2014* in table 8).

Differences from 2014 conditions at the outflow of the lake were nearly twice those downstream of the Golf Pond. These differences likely are due to the thermal load from the outflow from Reed Lake that flows into the Golf Pond, although solar heating on the west side of the pond also may be a factor. Aside from the *UpstreamMix* scenario, the scenarios with the greatest amount of cooling compared to 2014 conditions included heavy shade (*dynshd0.8* scenarios in table 9) and lower lake elevations (2.2–2.7 °F or 1.2–1.5 °C cooling downstream of the pond relative to 2014).

Simulated 7dADM outflow temperatures downstream of the pond under the two shading scenarios and all considered lake elevations are shown in figures 12*C–D*. Heavy shade scenarios (80 percent effective shade) resulted in cooler daily maximum temperatures than light shade (20 percent effective shade) and existing shade conditions. For example, at a lake water-surface elevation of 59.4 ft (18.1 m), the model estimated that providing 20 percent effective shade would decrease maximum daily stream temperatures below the Golf Pond by 0.5 °F (0.3 °C) for the period of study (table 9). For the same lake water-surface elevation, model estimates suggested that increasing effective shade to 80 percent would reduce maximum daily stream temperatures downstream of the Golf Pond by 1.4 °F (0.8 °C). During the hottest week of the period of study (week of July 31), model simulation results suggested that 80 percent effective shade would have reduced maximum daily stream temperatures downstream of the Golf Pond by 2.9 °F (1.6 °C)

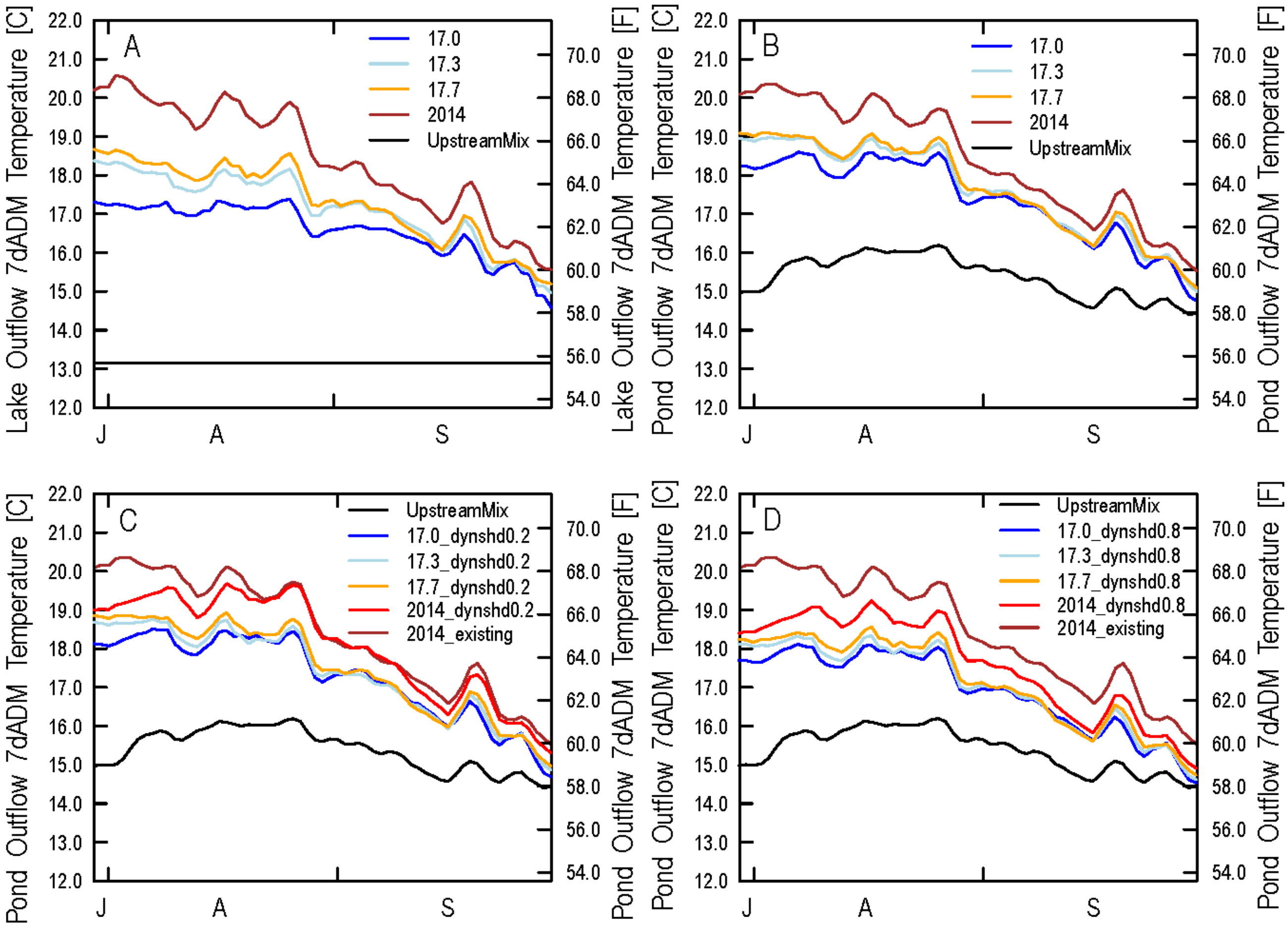

Figure 12. Graphs showing comparison of the 7-day average of the daily average maximum temperatures (7dADM) resulting from different lake surface elevation scenarios. Results shown for (A) total weighted average of outflow from Crystal Springs Lake (sites Spill and FL) using 2014 shading of Crystal Springs Lake, (B) outflow from the Golf Pond (site CSDS) using 2014 shading of Crystal Spring Lake, (C) outflow from the Golf Pond (site CSDS) using 20 percent shading of Crystal Spring Lake, and (D) outflow from the Golf Pond (site CSDS) using 80 percent lake shade of Crystal Spring Lake.

Figure 13 shows a comparison of the 7dADM averaged over the simulation period for each scenario. Downstream of the Golf Pond, only the *UpstreamMix* scenario resulted in 0 days in which the 7dADM exceeded the 18.0°C ODEQ criteria for rearing and migrating salmon (*NdaysAbove18* in table 9).

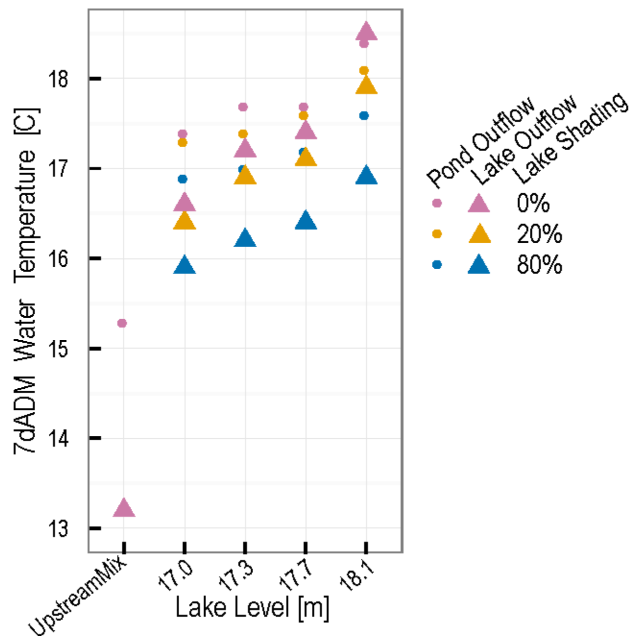

Figure 13. Graph showing comparison of 2-month simulation period of average 7-day moving average of daily maximum temperature under various scenarios downstream of Crystal Springs Lake (triangles) and the Golf Pond (circles), Portland, Oregon.

All management scenarios that included the existing dam structure resulted in cooling downstream of the Golf Pond that ranged between 0.5 and 2.7 °F (0.3 and 1.5 °C). Lowering the lake elevation to 58.1 ft (17.7 m) resulted in a similar amount of cooling (1.3 °F [0.7 °C]) as providing 80 percent effective shade to the lake (1.4 °F [0.8 °C]) (table 9). Management scenario *17.0_dynshd0.8* would provide the most water temperature cooling downstream of the Golf Pond (2.7 °F [1.5 °C]), but would also require the most extensive changes to the lake system- lowering the lake level to 55.8 ft (17.0 m) and requiring 80 percent effective shade. The cooling downstream of Gold Pond provided by management scenario *17.0_dynshd0.8* would be roughly double that provided by lowering the lake elevation to 17.7 m (58.1 ft) or providing 80 percent effective shade to the lake for the period of study; water temperatures downstream of the Golf Pond during the warmest week of the study period would have been 4.4 °F (2.4 °C) cooler.

Of the management scenarios evaluated, adding 10-m vegetation around the lake (20 percent effective shade) was the least-effective method for cooling water temperatures downstream of the Golf Pond. At 2014 lake levels, this shading option would cool the average water temperature for the period by 0.5 °F (0.3 °C). As lake water-surface elevations were lowered, the amount of cooling provided by 20 percent effective lake shade diminished in relation to the unshaded management scenarios at the same lake elevations. For example, at a lake elevation of 55.8 ft (17.0 m), the average water temperature downstream of the Golf Pond for the study period was only 0.2 °F (0.1 °C) cooler with 20 percent effective lake shade than without.

Potential Future Studies

The scenarios examined for this study included a range of lake elevations and the addition of shade trees that provide either minimal (20 percent) or thick (80 percent) shade coverage within 1 m of the lakeshore. The following model attributes could be altered to provide more insight into methods for achieving reductions in summer outflow temperature:

Shade

The scenarios evaluated in this report assumed mature trees (averaging 32.8 ft [10 m] in height). More detailed planting strategies could be developed and evaluated that consider different mixtures of vegetation and account for temporal changes in shading as it matures. For example, a Douglas-fir tree can grow 13–24 inches per year (approximately 0.3–0.6 m) and achieve heights of greater than 20 m (Arbor Day Foundation, 2015). Planting strategies could also consider other factors such as location (where do plantings provide maximum shade) and density (amount of density needed to achieve desired results). Additionally, different planting strategies could be evaluated for the Golf Pond.

Lake Water Elevations and Lake Bathymetry

In order to minimize model uncertainty, the scope of the project was limited to current bathymetric conditions. Model simulation results proved sensitive to bathymetric changes made during calibration. Consequently, introduction of a new bathymetry file and associated assumptions made to calculate a lake elevation/volume relation would have resulted in added uncertainty in model simulation results. Although new lake bathymetry inputs may result in less model accuracy, results still may provide general conclusions about expected changes in outflow temperature.

New scenarios could evaluate the effect of managing the water-surface elevation of Crystal Springs Lake daily and (or) seasonally to minimize residence times during warm periods of the year. Scenarios using a modified lake bathymetry could be developed that maintain the current lake depth but decrease the lake surface area. A smaller surface area to volume ratio could help reduce the outflow temperature.

Location of Springs Underneath Crystal Springs Lake

Assumptions were made regarding the location and size of the springs presumed to be underneath Crystal Springs Lake. Locating and measuring the temperature and discharge volume of those springs could reduce uncertainties in future iterations of the model.

The Golf Pond and Reed Lake

In the scenarios evaluated in this study, the Golf Pond was left unaltered and Reed Lake was not modeled. Much of the decrease in temperature between the 2014 conditions and the potential management scenarios was lost due to heat added in the Golf Pond. For example, during the warmest week of the period evaluated (July 31), average outflows from the lake and pond were 68.5 and 68.4 °F, respectively (20.3 and 20.2 °C). In the scenario *17.3_dynshd0.8,* outflow from the lake was reduced to 63.0 °F (17.2 °C), and 7dADM values did not exceeded the 64.4 °F (18.0 °C) ODEQ criteria for rearing and migrating salmon. However, outflow from the pond during that same week was 64.6 °F (18.1 °C) (1.6 °F or 0.9 °C greater than lake outflow), and 21 values of 7dADM exceeded that same threshold. Some of this warming is due to the inflow from Reed Lake. Model scenarios could be done that add shade to the Golf Pond, or that remove or modify the pond. A more extensive study could investigate the potential of altering the bathymetry of Reed Lake.

Fish Habitat Suitability Simulation

A module within CE-QUAL-W2 allows for the computation of the volume of fish habitat available based on temperature and dissolved oxygen (DO) targets for any particular fish species of interest (Cole and Wells, 2015). Currently, the Crystal Springs Lake and the Golf Pond models are not calibrated to simulate DO. Continuous DO was measured by BES at the CLM and CSDS sites during summer 2014 and could be used to calibrate the existing CE-QUAL-W2 model for DO with an additional effort. Expansive algal populations were observed in the lake during summer 2014, which most likely are the primary source of the large diurnal range in DO in the lake. Calibration of a DO model might be easier with relative abundance counts of algal groups through the summer in the lake so that various growth and decay rates could be incorporated into such a model. Simulation of available fish habitat could be beneficial as scenarios are refined and planning proceeds. This added capability could allow for an improved and fish-centric view of the lake and pond system, as DO is an important determinant of available fish habitat. Large algal populations may affect water temperature.

Effects to Johnson Creek

Scenario results from this study could be used to assess the potential downstream water temperature effects to Johnson Creek. Downstream warming estimates could be applied from the Golf Pond to the confluence with Johnson Creek during summer. This could be followed by a weighted balance calculation between the two streams and result in a hypothetical stream temperature in Johnson Creek under various management scenarios.

Summary

Water temperature and streamflow data were collected during summer 2014 in and around Crystal Springs Lake to better understand the effect of the system on downstream temperatures along Crystal Springs Creek. A two-dimensional hydrodynamic model (CE-QUAL-W2) was developed to investigate potential temperature mitigation options. Model grids were developed to closely resemble bathymetric data acquired during a 2014 survey. When possible, data collected in summer 2014 were used as boundary conditions for the model. Discrepancies between measured inflow to and outflow from the lake were assumed to be largely from unknown springs underneath the lake and accounted for about 46 percent of the total outflow from the lake. The calibrated model simulated surface water-elevations within 0.06 foot (0.02 meter) and outflow water temperatures within 1.08 °F (0.60 °C).

To better inform the planning process and explore potential temperature mitigation options, 12 potential management scenarios were evaluated. A scenario in which no dam or lake is present was also analyzed in order to evaluate the upper bound of potential change. Temperatures were simulated at four lake elevations (including current conditions) and at three levels of shade (including current conditions). The Golf Pond was unaltered in all scenarios.

Management scenarios resulted in 7dADM outflow temperatures from the lake that were, on average, 2.0–4.7 °F (1.1–2.6 °C) cooler than 2014 conditions for the period of analysis and 7dADM outflow temperatures below the pond that were, on average, 1.3–2.7 °F (0.7–1.5 °C) cooler. The increase in relative temperature between the lake and the pond is due to the mixing with warmer water from Reed Lake and possibly from sunlight exposure on the west side of the pond, although overall residence time in the pond is short (about 1 hour). Outflows from the lake were cooler with both decreased lake levels and increased shade. During 2014, lake outflow exceeded the 7dADM temperature ODEQ TMDL standard of 64.4 °F (18.0 °C) on 43 days. A few potential management scenarios produced lake outflows that reduced the number of days in exceedance of the TMDL to zero throughout the summer. . However, only one scenario (without the dam in place) produced pond outflow that met the TMDL standard throughout the summer study period.

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