Prepared in cooperation with the U.S. Army Corps of Engineers

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Open-File Report 2015–1012

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

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

$$°F=(1.8×°C)+32.$$

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

$$°C=(°F-32)/1.8.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

Abbreviations and Acronyms

Name	Description
7dADM	7-day moving average of the daily maximum
ATU	accumulated thermal unit
BiOp	biological opinion
CE-QUAL-W2	2- dimensional hydrodynamic and water-quality model
RM	river mile
RO	regulating outlet
TMDL	total maximum daily load
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

Water temperature models of Detroit Lake, Big Cliff Lake, and the North Santiam River in northwestern Oregon were used to assess the potential for a hypothetical structure with variable intake elevations and an internal connection to power turbines at Detroit Dam (scenario *SlidingWeir*) to release more natural, pre-dam temperatures year round. This hypothetical structure improved outflow temperature control from Detroit Dam while meeting minimum dry-season release rates and lake levels specified by the rule curve specified for Detroit Lake.

A water temperature target based on long-term, without-dams temperature estimates was developed and used to guide the Detroit Lake model to blend releases from the user-defined outlets at Detroit Dam. Simulations that included warm surface water releases during the spring and summer, and cool, deep hypolimnetic water releases later during autumn typically met the temperature target. Immediately downstream of Detroit Dam, these simulations resulted in temperatures within the range of the without-dams temperature estimates for most of the year until about November. The minimum release rates of flow imposed at Detroit Dam during late summer and early autumn exceeded unregulated, without-dams flow estimates. This higher flow led to temperatures near the low end of the without-dams temperature range 46.3 river miles downstream at Greens Bridge from July to September; the high flows released from Detroit Dam were less susceptible to downstream warming than the low unregulated flows. Simulations that blended warm and cool water from different outlets at Detroit Dam resulted in less daily temperature variation compared to the without-dams scenarios as far downstream as Greens Bridge.

Estimated egg-emergence days for endangered Upper Willamette River Chinook salmon (*Oncorhynchus tshawytscha*) and Upper Willamette River winter steelhead (*Oncorhynchus mykiss*) were assessed for all scenarios. Estimated spring Chinook fry emergence under *SlidingWeir* scenarios was 9 days later immediately downstream of Big Cliff Dam, and 4 days later at Greens Bridge compared with existing structural scenarios at Detroit Dam. Despite the inclusion of a hypothetical sliding weir at Detroit Dam, temperatures exceeded without-dams temperatures during November and December. These late-autumn exceedances likely represent the residual thermal effect of Detroit Lake operated to meet minimum dry-season release rates (supporting instream habitat and irrigation requirements) and lake levels specified by the current (2014) operating rules (supporting recreation and flood mitigation).

Introduction

Detroit Dam was constructed in 1953 by the U.S. Army Corps of Engineers (USACE) on the North Santiam River in northwestern Oregon and resulted in the formation of Detroit Lake (fig. 1). The North Santiam River drains an area on the western slopes of the Cascade Range and is one of several major tributaries to the Willamette River. Detroit Dam is the tallest dam (463 ft) in the Willamette River Basin and impounds 455,100 acre-ft of water at full pool, making it one of the largest reservoirs in the basin. The small re-regulating dam downstream of the Detroit and Big Cliff Dams ensures steady streamflows in the North Santiam River and allows Detroit Dam's power generating facility (and releases) to be turned on and off during the course of a day to meet peak electrical demands. Big Cliff Lake is much smaller than Detroit Lake, with a reservoir volume of 6,450 acre-ft at full pool. The Big Cliff–Detroit Dam complex typically generates among the most hydroelectric power of Willamette River basin USACE facilities, and Detroit Lake ranks as one of the most important recreational resources among the 13 reservoirs managed by USACE in the Willamette Project.

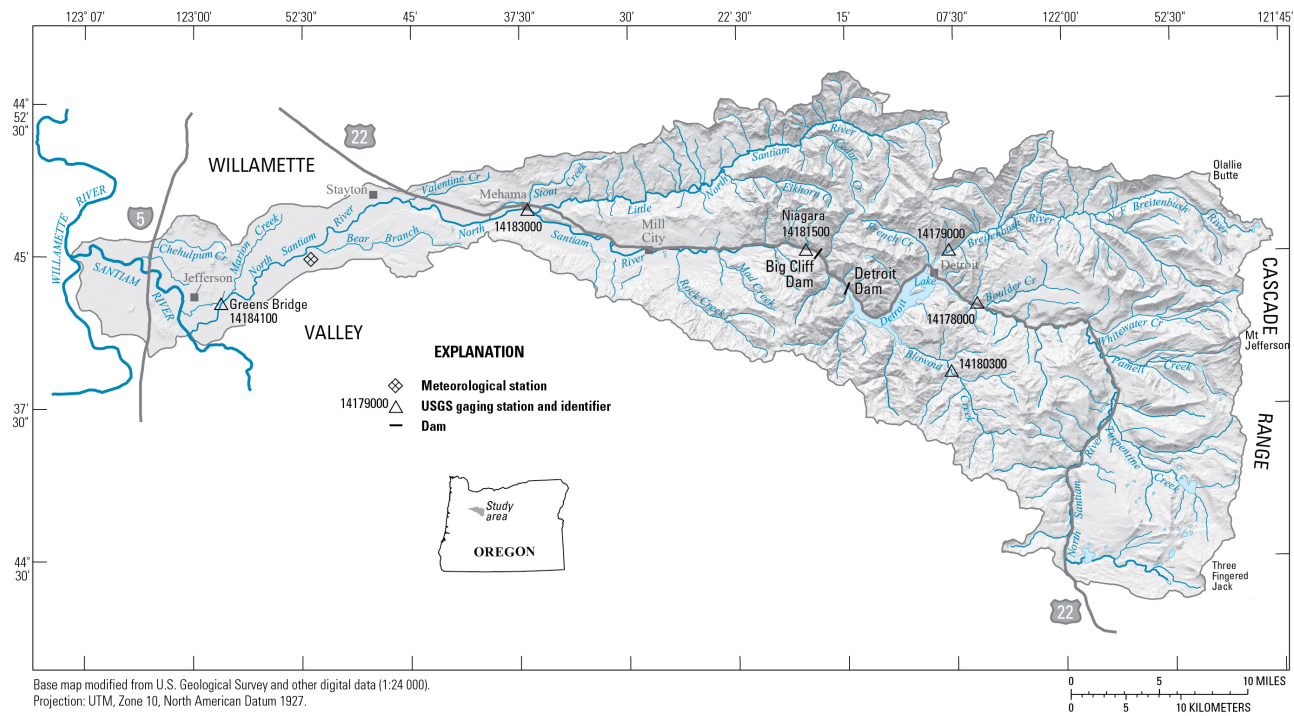

Figure 1. Map showing North Santiam and Santiam Rivers and the North Santiam River Basin, northwestern Oregon. (Modified from Sullivan and Rounds, 2004.)

Prior to 2007, power generation was a high priority for the Big Cliff–Detroit Dam complex, and releases from Detroit Dam generally were routed through the power penstocks (centerline elevation 427.6 m or 1,403 ft) except for times when excess flows were released through the upper regulating outlets (ROs) (center-line elevation 408.4 m or 1,340 ft) or over the spillway (crest elevation 469.7 m or 1,541 ft). During those years, midsummer releases were unseasonably cold because the power penstocks are located 166 ft below Detroit Lake's full-pool level, well below the thermocline at that time of year. Releases from that depth allowed summer solar energy inputs to accumulate in a growing layer of warm water at the lake surface. Drawdown of the lake in September to make room for winter flood storage typically resulted in warmer waters at the level of the power penstocks and unseasonably warm releases in late summer and autumn. The thermal effects of Willamette River Basin dams have been quantified in recent modeling studies, and the effects can extend for many miles and many days of travel time downstream of the dams (Rounds, 2010).

The North Santiam River and its tributaries (fig. 1) provide habitat for endangered Upper Willamette River Chinook salmon (*Oncorhynchus tshawytscha*) and Upper Willamette River winter steelhead (*Oncorhynchus mykiss*). The Oregon Department of Environmental Quality has set maximum water-temperature standards for stream reaches in Oregon, including the North Santiam and Santiam Rivers, to protect certain life stages of these sensitive fish (Oregon Department of Environmental Quality, 2009). These criteria are based on the 7-day moving average of the daily maximum (7dADM) water temperature. For example, the North Santiam River is designated as core cold-water habitat for June 16–August 31 annually, with the 7dADM water temperature not to exceed 16.0 °C. A stricter 13.0 °C criterion is in place for salmon and steelhead spawning habitat during September 1–June 15. Farther downstream, the Santiam River is designated as salmon and trout rearing and migration habitat, with a maximum 7dADM water temperature of 18.0 °C for May 16–October 14, and salmon and steelhead spawning habitat for October 15–May 15, with the 13 °C maximum criterion (Oregon Department of Environmental Quality, 2009). Unusually warm temperatures have been associated with negative impacts to various life stages of spring Chinook salmon, including high prespawn mortality (Keefer and others, 2010), delayed migration (Goniea and others, 2006; Angilletta and others, 2008), and premature fry emergence (U.S. Army Corps of Engineers, 2009). To protect and enhance these beneficial uses and habitats, the National Marine Fisheries Service wrote a 2008 Willamette Basin Biological Opinion (BiOp) that, among other things, urges the USACE to assess the feasibility of developing project-specific alternatives for achieving long-term temperature control at the Big Cliff–Detroit Dam complex (National Marine Fisheries Service, 2008). The USACE is in the process of evaluating alternatives for both current and long-term downstream temperature management and fish passage at many of the dams in the Willamette Project.

Detroit Dam is an excellent facility for the USACE to test strategies for downstream temperature management because the dam has outlets at several fixed elevations, allowing water to be released from multiple depths and blended to meet a downstream temperature target. In particular, the release of warm water over the spillway in midsummer and cool water from deep in the lake in late summer and early autumn can help mitigate problems associated with water temperatures that otherwise would be too cold or too warm for fish. Since 2007, USACE has released water through the spillway, the upper ROs, and the power penstocks to improve downstream fish habitat during the various life stages of endangered salmonid fish species, while at the same time balancing the need to generate hydropower.

To help evaluate potential dam operation strategies and future structural options, the USACE can use predictions from several models that simulate water temperature in Detroit Lake, Big Cliff Lake, and the North Santiam River. The U.S. Geological Survey (USGS) previously constructed and calibrated a model of Detroit Lake to examine water temperature and suspended-sediment conditions in the lake and downstream (Sullivan and others, 2007). The model was built using CE-QUAL-W2, a two-dimensional, laterally averaged hydrodynamic and water-quality model from USACE (Cole and Wells, 2002) that has been widely applied to river and reservoir systems around the world. The USGS Detroit Lake model was calibrated to conditions that occurred during calendar years 2002 and 2003 and also was tested for high-flow conditions during winter 2005–06. The model and many results are available at *http://or.water.usgs.gov/santiam/detroit_lake/* (U.S. Geological Survey, 2013).

The USGS Detroit Lake model was originally built with a modification of CE-QUAL-W2 version 3.12 (Sullivan and others, 2007) but has since been upgraded to version 3.7 (Cole and Wells, 2011) and modified to enhance the algorithm that allows a model user to easily estimate the release rates that are required from different dam outlets to achieve a time series of downstream temperature targets (Rounds and Sullivan, 2006; Buccola and others, 2012; Rounds and Buccola, 2015). In this way, dam operations can be forecast to meet certain downstream fish habitat criteria at different times of the year. A CE-QUAL-W2 model of Big Cliff Lake (Buccola and others, 2012) and a HEC-RAS model of the North Santiam and Santiam Rivers (Stonewall and Buccola, 2015) also have been constructed and calibrated. Using those models, predicted flows and water temperatures from the Detroit Lake model can be translated downstream to evaluate how temperatures change in the 60.9 mi of river downstream of Detroit Dam before the Santiam River joins the Willamette River.

Purpose and Scope

The purpose of this report is to provide water temperature estimates throughout the North Santiam River system from Detroit Dam to Greens Bridge (46.4 mi downstream of Detroit Dam, near the junction of the North Santiam and South Santiam Rivers) under a range of environmental conditions and potential structural changes at Detroit Dam. Model results presented in this report are intended to provide insight into what potential temperatures may result from a hypothetical temperature control structure at Detroit Dam for the purpose of improving current downstream temperature conditions for fish in the North Santiam River. Biological impacts related to water temperature are addressed during spring and autumn, which are critical seasons for threatened/endangered salmon and steelhead habitat. The results published in this report augment results in Buccola and others (2012).

A range of environmental conditions that represent "*cool/wet,*" "*normal,*" and "*hot/dry*" hydrological and meteorological conditions based on historical data and defined by Buccola and others (2012) were used for all model scenarios in this study. Results of simulations with the temperature control structure at Detroit Dam were compared at various points along the North Santiam River downstream of the dams with results from other simulations that included the existing structures at Detroit Dam and results from scenarios that were based on without-dams estimated temperatures as documented by Buccola and others (2012).

This study used previously developed CE-QUAL-W2 models of Detroit Lake (Sullivan and others, 2007) and Big Cliff Lake (Buccola and others, 2012) for all simulations of water discharge and temperature in the reservoirs. An enhanced blending routine was added to CE-QUAL-W2 version 3.7 (Rounds and Buccola, 2015) and used for all model simulations of Detroit Lake. A one-dimensional HEC-RAS flow and temperature model of the North Santiam River (Stonewall and Buccola, 2015) was used for all simulations of water discharge and temperature downstream of Big Cliff Dam.

Methods

Flow and Temperature Models

Two separate CE-QUAL-W2 models were used in this study to simulate Detroit and Big Cliff Lakes. The North Santiam River downstream of Big Cliff Dam was simulated using the HEC-RAS model with its water-quality module (Stonewall and Buccola, 2015). For this study, a customized version 3.7 CE-QUAL-W2 model (Rounds and Buccola, 2015) was used for temperature models at Detroit and Big Cliff Lakes. Big Cliff Lake is a small re-regulating reservoir just downstream of Detroit Dam, and its operation has a small effect on water temperature at some times of the year. HEC-RAS model version 4.10 (Brunner, 2010) was used to develop a one-dimensional flow and temperature model for the North Santiam River and calibrated to conditions in 2011 and 2002 with emphasis on the low-flow period during summer and autumn (Stonewall and Buccola, 2015).

Environmental Scenarios

Three distinctly different environmental forcing scenarios named *cool/wet, normal,* and *hot/dry* were originally documented by Buccola and others (2012) to capture a wide range of possible streamflow, water temperature, and meteorological conditions. These environmental scenarios consisted of the measured conditions from various timeframes spliced together (table 1). All inflows used in this study (including precipitation and distributed tributaries) and meteorological inputs remained identical to those original environmental scenarios documented by Buccola and others (2012). In brief, inflow discharge and temperature were mostly measured at USGS sites near Detroit Lake. Air temperature, dew-point temperature, wind speed, and wind direction were measured near Stayton, Oregon, while solar radiation and precipitation were measured at Eugene and Detroit, Oregon, respectively.

Table 1. Description of environmental scenarios, North Santiam River, northwestern Oregon.

[From Buccola and others (2012), table 2]

Environmental forcings	Measured time-frame		Concatenate date (month/day)
	Spring/Summer	Autumn/Winter	
cool/wet	2009	2006	10/12
normal	2006	2009	9/27
hot/dry	2005	2002	9/27

Without-Dams Water Temperature Estimation

Hourly water temperatures for the North Santiam River were estimated at two locations: (1) Big Cliff Dam (river mile [RM] 58)- for a "without-dams" scenario, and (2) Detroit Dam [RM 60.9] to develop a temperature target for the CE-QUAL-W2 model scenarios and described further in section, "Temperature Targets." Without-dams estimates at Big Cliff Dam (where Detroit and Big Cliff Dams do not exist in this simulation) for *cool/wet, normal,* and *hot/dry* environmental scenarios followed methods documented in Buccola and others (2012). The estimates were computed using a simple mass and energy balance approach combined with a nominal downstream warming rate applied during summer, following methods documented by Rounds (2010).

Temperature Targets

Recent developments of the blending algorithm within CE-QUAL-W2 allow a user to impose a time-series of temperature targets that the model will try to meet, mixing outflow from the available outlets at the dam (Rounds and Buccola, 2015). Previous studies have used temperature targets developed by USACE for the McKenzie River system downstream of another dam (Cougar Dam on the South Fork McKenzie River) as representative of the conditions needed to support a restoration of uses by endangered fish (Buccola and others, 2012; U.S. Army Corps of Engineers, 2012). To compare this previously applied set of targets with temperatures that may better represent the North Santiam subbasin, a new set of targets were developed based on the long-term maximum of measured daily average temperatures from USGS stations on the North Santiam River below Boulder Creek (station 14178000) and the Breitenbush River above French Creek (station 14179000), and Blowout Creek near Detroit (station 14180300). A flow-weighted average of temperatures from these three stations was computed using the following equation:

$$T_{est} = (Q_{NS}\,T_{NS} + Q_{BB}\,T_{BB} + Q_{BL}\,T_{BL}) / (Q_{NS} + Q_{BB} + Q_{BL}), \quad (1)$$

where

T_{est} is mixed water temperature estimate, in degrees Celsius,

Q_{NS} is measured streamflow in the North Santiam River at station 14178000, in cubic feet per second,

T_{NS} is measured water temperature in the North Santiam River at station 14178000, in degrees Celsius,

Q_{BB} is measured streamflow in the Breitenbush River at station 14179000, in cubic feet per second,

T_{BB} is measured water temperature in the Breitenbush River at station 14179000, in degrees Celsius,

Q_{BL} is measured streamflow in Blowout Creek at station 14180300, in cubic feet per second, and

T_{BL} is measured water temperature in Blowout Creek at station 14180300, in degrees Celsius.

The long-term (water years 1998–2013) maximum of these daily mean water temperatures for each day (that is, the maximum of the daily mean values for each January 1 day from 1998 to 2013, and so on) then were computed and adjusted to account for the instream warming that most likely occurred as water traverses the 9-mi reach between the upstream end of Detroit Lake (where these tributaries were assumed to join and mix) and Detroit Dam. From November 1 to April 13, or any time of the year when water temperatures were less than 6 °C, no instream warming adjustments were made to water temperature estimates. From April 14 to October 31, a downstream warming rate was applied as a function of the mixed temperature estimate. All water temperature estimates greater than 14 °C were increased by 0.99 °C to account for a nominal maximum downstream warming rate of 0.11 °C/mi over 9 mi of distance. This maximum downstream warming rate was based on historical data (Moore, 1964, 1967) as well as previous water-temperature modeling in the North Santiam River in the 4 mi just downstream of Big Cliff Dam (Rounds, 2010). Water-temperature estimates less than 14 °C but greater than 6 °C were increased to account for some downstream warming, but less than the maximum rate of 0.11 °C/mi, using the following linear interpolation:

$$T_{final} = T_{est} + 0.99\,(T_{est} - 6.0) / (14.0 - 6.0), \quad 6.0 \le T_{est} \le 14.0. \quad (2)$$

To create a continuous time-series temperature target for the model, this time-series was smoothed using a centered 30-day moving average (fig. 2). When applied with the CE-QUAL-W2 temperature model to scenarios in this study, the final version of this temperature target specified the peak value from this smoothed time series (15.9 °C) from Julian day 1 to 216 (January 1 to August 4). This change essentially directed the model to release as much warm water as possible from the lake during the spring and early summer, while saving cool, deeper water for release later in autumn.

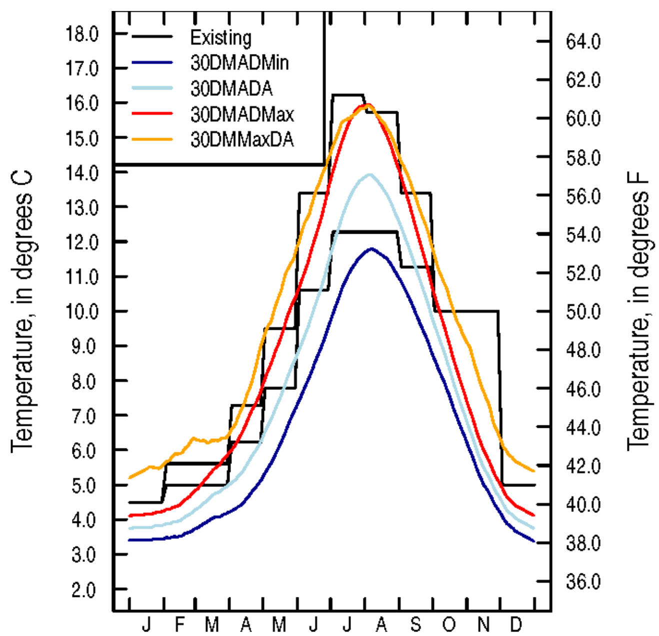

Figure 2. Graph showing temperature targets for the North Santiam River downstream of Detroit Dam, northwestern Oregon. Existing, target used for the McKenzie River, Oregon; 30DMADMin, 30-day moving average of long-term daily minimum; 30DMADA, 30-day moving average of long-term average daily; 30DMADMax, 30-day moving average of long-term daily maximum; 30DMMaxDA, 30-day moving maximum of average daily. All targets except for Existing are based on flow-weighted measured temperatures of the Detroit Lake inflows and were warmed by 0.11 °C/mi for 9 mi during summer months.

Dam Outflow Estimation

Detroit Dam

The total release rates (outflows) from Detroit Dam were set to adhere to the following conditions:

1. Releases from Detroit Dam should meet minimum and maximum flow requirements as specified by the BiOp (National Marine Fisheries Service, 2008), with some exceptions during March and April in the *hot/dry* scenario (table 2).
2. Computed water levels in Detroit Lake should not exceed the reservoir rule curve (the operational target for the lake water-surface elevation throughout the year) for more than 5 days when the lake is at full-pool elevation.
3. Total outflow should be based on the use of one (*Base*) or two (*HighPeak*) turbines at Detroit Dam and concentrated for specific hours of the day (table 3) to simulate "power peaking" operations. The *Base* operational scenario group as described in Buccola and others (2012) was used as a reference condition.

Table 2. Minimum and maximum outflow requirements for operational scenarios at Detroit Dam, North Santiam River, northwestern Oregon.

[Flows are daily mean streamflow, in cubic feet per second (ft^3/s). Altered flows for the *hot/dry* scenario are indicated by the numbers in *italics*]

Month/Day	Operational scenario group minimum flows (ft^3/s)		
	cool/wet	***normal***	***hot/dry***
Minimum flow			
Jan. 1	1,200	1,200	1,200
Feb. 1	1,000	1,000	1,000
Mar. 1	1,000	1,000	1,000
Mar. 16	1,500	1,500	*1,000*
Apr. 1	1,500	1,500	*1,000*
Apr. 16	1,500	1,500	1,500
May 1	1,580	1,580	1,580
May 16	1,580	1,580	1,580
June 1	1,280	1,280	1,280
July 1	1,280	1,280	1,280
July 16	1,080	1,080	1,080
Sept 1	1,500	1,500	1,500
Oct. 16	1,200	1,200	1,200
Dec. 1	1,200	1,200	1,200
Dec. 31	1,200	1,200	1,200
Maximum flow			
Jan. 1	15,000	15,000	15,000
Sept. 1	3,000	3,000	3,000
Sept. 30	3,000	3,000	3,000
Dec. 31	15,000	15,000	15,000

Table 3. Operational scenario group descriptions, Detroit Dam, North Santiam River, northwestern Oregon.

[(ft^3/s, cubic feet per second]

Operational scenario groups	Power peaking operation maximum flow (ft^3/s)	Order of peaking hours in each day	Maximum total outflow (ft^3/s)
Base	2,472	0600–2200	5,000
HighPeak	4,900	(1) 1700–2400	5,600
		(2) 0500–1200	
		(3) 1300–1600	
		(4) 0100–0400	

Big Cliff Dam

A method of estimating outflows at Big Cliff Dam was developed to simulate outflows that closely approximated typical dam operations while balancing inflows and outflows and recreating relatively stable lake levels in Big Cliff Lake. The outflow at Big Cliff Dam initially was assumed to be a moving daily average of the total inflow to Big Cliff Lake. Efforts were made to limit the pool elevation in Big Cliff Lake between its minimum conservation pool (360.3 m or 1,182.0 ft) and full pool (367.5 m or 1,205.8 ft) (further discussed in section, "Big Cliff Lake Water Balance and Heat Exchange"). The addition of a distributed tributary inflow (median discharge of approximately 35 ft^3/s) to the Big Cliff model helped to achieve relatively constant lake levels while accounting for unmeasured tributary inflows. An iterative process then was used to adjust this distributed tributary based on the difference between subsequent modeled water-level elevations and a mean pool elevation of 362.1 m or 1,188 ft. This resulted in simulations of Big Cliff Lake that both resembled current operating elevation rules and led to simulations with a relatively constant pool elevation, which is acceptable for the purposes of this study.

CE-QUAL-W2 Model Structure Parameters

Within the model, the "w2_con.npt" and "w2_selective.npt" files define the outlet parameters used by the blending algorithm. For this study, parameters related to structure centerline elevation and width (STR ELEV and STR WIDTH in the w2_con.npt file) were adjusted from original values in Sullivan and others (2007). All structures were assigned STR SINK values of "LINE", while STR WIDTH values were varied (table 4). Other parameters in the w2_selective.npt file of the modified version of CE-QUAL-W2 (Rounds and Buccola, 2015) related to the preference of outlets (PRIORITY), minimum flow fraction (MINFRAC), floating outlet depth below the water surface (DEPTH), maximum flow limitation (MAXFLOW), and maximum head limit (MAXHEAD) for a given outlet also were adjusted for this study (table 4).

Of primary importance to this report was the simulation of a hypothetical temperature control structure at Detroit Dam in which a weir gate floats 2.3 m below the lake surface (named "upper weir" with DEPTH=2.3 m in structural scenario *SlidingWeir;* table 4). This hypothetical upper weir gate was assumed to resemble some characteristics of the existing upper RO (STR WIDTH=6.8 m), with a minimum outflow of 11.3 m^3/s (MINFRAC = -11.3 in table 4**)** that is routed through the dam to the hydropower turbines in such a way that releases from this surface outlet (typically warmer than that of the water near the power penstocks) would not be limited by hydropower demands. A lower weir gate with centerline outlet elevation close to the elevation of the existing upper RO (STR ELEV = 408.4 m) was blended with this upper weir gate (upper weir and lower weir both have PRIORITY = 1 in table 4**)**. The *SlidingWeir* scenario also included the existing spillway and upper RO outlets at Detroit Dam, used only as overflow, when total outflow at the dam exceeded the powerhouse maximum (MAXFLOW = 158.5 m^3/s in table 4). To ensure that the upper and lower weir outlets did not release more than a combined 158.5 m^3/s (5,600 ft^3/s), the time series of overflow values (total Detroit Dam outflow in exceedance of 158.5 m^3/s) for the spillway/upper RO were specified in the outflow boundary condition file and both outlets were given PRIORITY= -1 (table 4). A priority of -1 tells the model to include those outflows in its attempt to meet the user-specified target temperature for the releases, but that these flows are set by the user and cannot be changed by the model's blending algorithm.

For the Detroit Lake model, two reference scenarios were included—one in which no blending of releases occurred (all outflow was directed to the power penstocks – named *NoBlend*) and another in which only the existing outlets at Detroit Dam were used (spillway, power penstocks, and upper RO – named *Existing*). Under *Base* operational scenarios, a minimum fraction (40 percent) of the outflow in the *Existing* scenario was routed to the power penstocks for power generation (MINFRAC=0.4, PRIORITY=1 in table 4) while the remaining outflow was blended between the power penstocks, the spillway (PRIORITY = 2**)** when lake levels were above the spillway crest (STR ELEV=469.7 m in table 4), and the upper RO (PRIORITY=2) when lake levels were below 471 m (STR ELEV=408.4 m, MAXHEAD=61 m in table 4). The TSSHARE input to was set to OFF in this *Base* scenario, causing the model to choose either the spillway or the upper RO, but never both at the same time, as a preferred outlet to blend releases with the power penstocks.

Table 4. Structural scenario group descriptions and model parameter settings, Detroit Dam, North Santiam River, northwestern Oregon.

[STR ELEV and STR WIDTH are parameters specified in the w2_con.npt file, while PRIORITY, MINFRAC, DEPTH, MAXFLOW, and MAXHEAD are parameters specified in the w2_selective.npt file. Negative PRIORITY values indicate that outflow boundary conditions for the structure are used. Negative MINFRAC values indicate a specific minimum flow in cubic meters per second [m^3/s]]

Structural scenario groups	Stucture name	Model parameter						
		STR ELEV (meters)	STR WIDTH (meters)	PRIORITY	MINFRAC	DEPTH (meters)	MAXFLOW (m^3/s)	MAXHEAD (meters)
SlidingWeir	upper weir	481.3	6.8	1	-11.3	2.3	158.5	0
	spillway	469.7	25	-1	0	0	0	0
	lower weir	408.4	6.8	1	0	0	158.5	0
	upper RO	410	6.8	-1	0	0	158.5	0
Existing	spillway	469.7	25	2	0	0	0	0
	power penstocks	427.6	6.8	1	0.4	0	0	0
	upper RO	408.4	6.8	2	0	0	158.5	61
NoBlend	power penstocks	427.6	6.8			not applicable		

The two operational scenarios described in table 3 were combined with three structural scenarios (table 4), projected onto the three environmental forcing conditions of *cool/wet*, *normal*, and *hot/dry*, and combined with a set of temperature target requirements to produce the model scenarios of interest (table 5). The combination of these three conditions—operational scenario, structural scenario, and environmental scenario—fully describes the major differences between the model scenarios and provides a consistent naming convention.

Table 5. Specification and naming convention of model scenarios, Detroit Dam, North Santiam River, northwestern Oregon.

[Scenario identifier: c, cool/wet; n, normal; h, hot/dry]

Structural scenarios	Operational scenarios	Scenario identifier Environmental forcings		
		cool/wet	*normal*	*hot/dry*
NoBlend	*Base*	*c1*	*n1*	*h1*
Existing	*Base*	*c2*	*n2*	*h2*
SlidingWeir	*HighPeak*	*c3*	*n3*	*h3*

North Santiam River Model Setup

Release flows and temperatures from the CE-QUAL-W2 Big Cliff Lake model were used as hourly time-series inflow boundary conditions to the North Santiam River model (Stonewall and Buccola, 2015). Tributary inflow and temperature inputs, and meteorological input data sources were similar to those described by Stonewall and Buccola (2015).

Results

Detroit Dam Release Rates and Simulated Lake Elevations

Before comparing modeled outflow temperatures from the various scenarios, it is helpful to compare the imposed release rates (outflows) and simulated lake water-surface elevations in each of the operational scenarios, because the timing of the rule curve can contribute greatly to the resulting temperature regime in the lake. Both *Base* and *HighPeak* operational scenarios generally led to simulated lake levels that closely matched the USACE rule curve for most of the year. Some deviations from the rule curve existed in January–March as lake levels were rising and in mid-July–mid-October as minimum release requirements exceeded inflows (figs. 3, 4, and 5). The *HighPeak* operational scenario release rates led to minor lake elevation differences compared to *Base* operations, primarily January–March under *normal* and *cool/wet* environmental scenarios (fig. 5). Lake elevations in *hot/dry* scenarios were lower than *normal* and *cool/wet* scenarios year round.

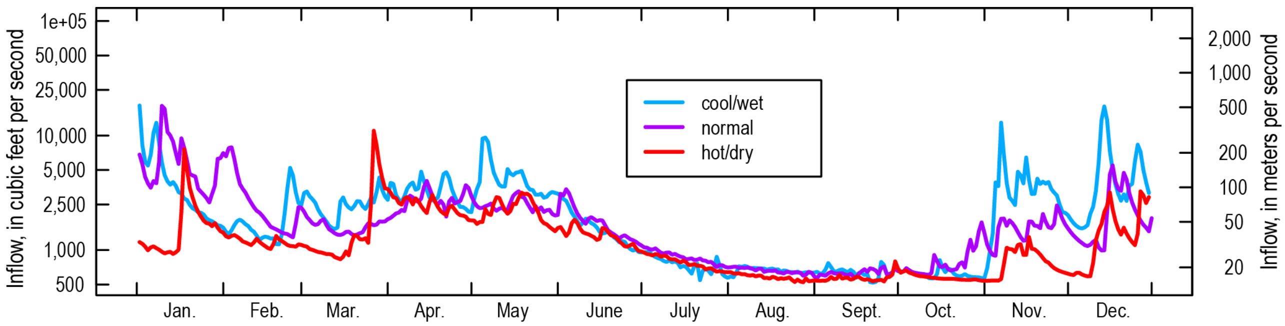

Figure 3. Graph showing simulated total inflows under all environmental scenarios, North Santiam River, northwestern Oregon.

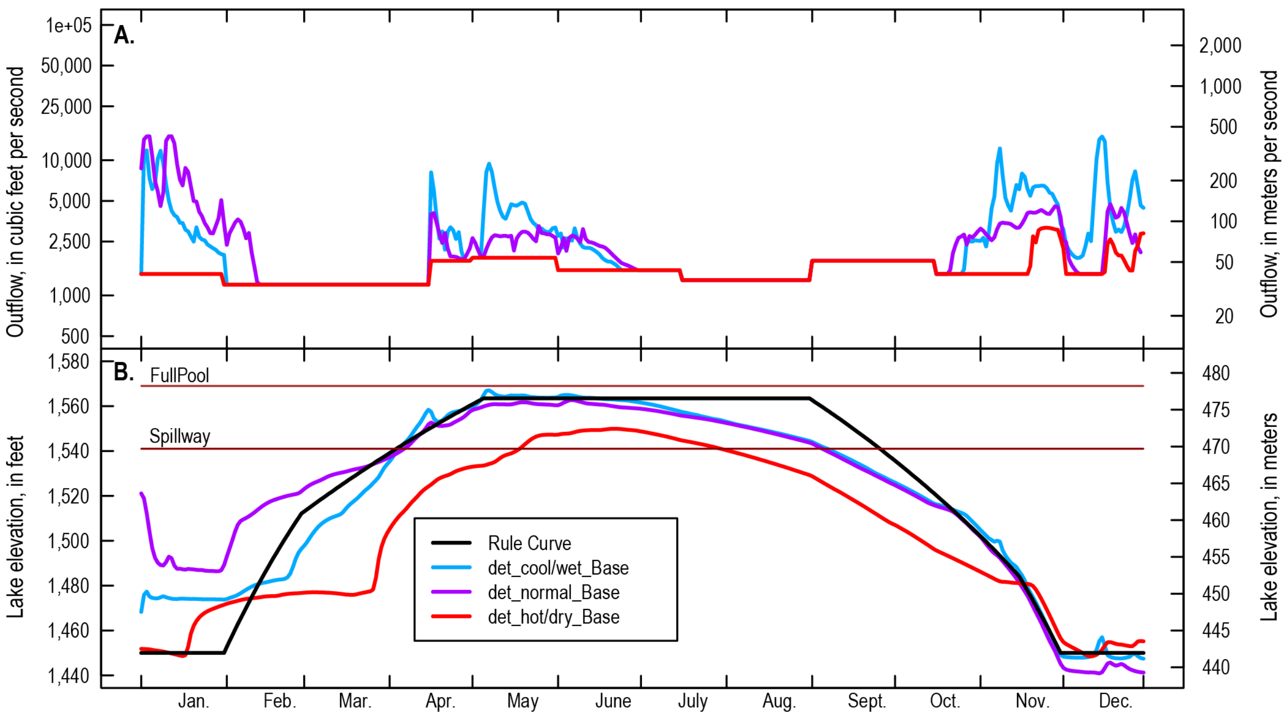

Figure 4. Graphs showing simulated *Base* operational scenario (imposed conditions for scenarios *c1*, *n1*, *h1, c2, n2, h2*) for (A) total outflows and (B) water-surface elevation and rule curve, North Santiam River, northwestern Oregon.

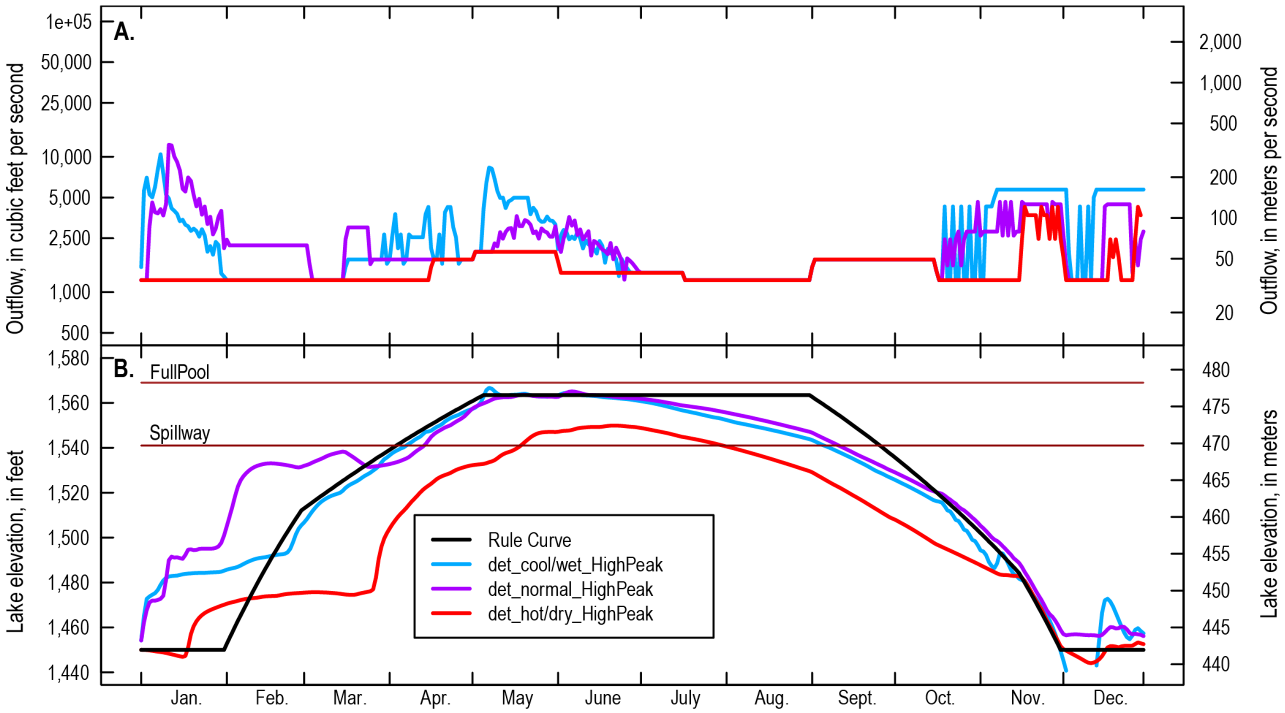

Figure 5. Graphs showing simulated *HighPeak* operational scenario (imposed conditions for scenarios *c3, n3, h3*) for (A) total outflows and (B) water-surface elevation and rule curve.

Detroit Dam Release Temperatures

Simulated temperatures from the *NoBlend* structural scenario with the *Base* operational scenario reflect the result of typical dam operations at Detroit Dam prior to 2007 and serve as a basis to compare other structural and operational scenario outcomes (fig. 6A). As *NoBlend* scenarios were limited to only one outlet (power penstocks), the resulting release temperatures from Detroit Dam during summer months were as much as 7 °C below the temperature target ("Rule Curve" in fig. 6) while autumn temperatures were as much as 6 °C above the target. The power penstocks (centerline 427.6 m elevation) can be about 50 m below the surface of Detroit Lake during the summer, which leads to the release of deeper, cool water at this time. As the lake is drawn down in September–November, warm surface water not yet released during the summer is drawn closer to the power penstocks, resulting in unseasonably warm autumn release temperatures under the *NoBlend* scenario.

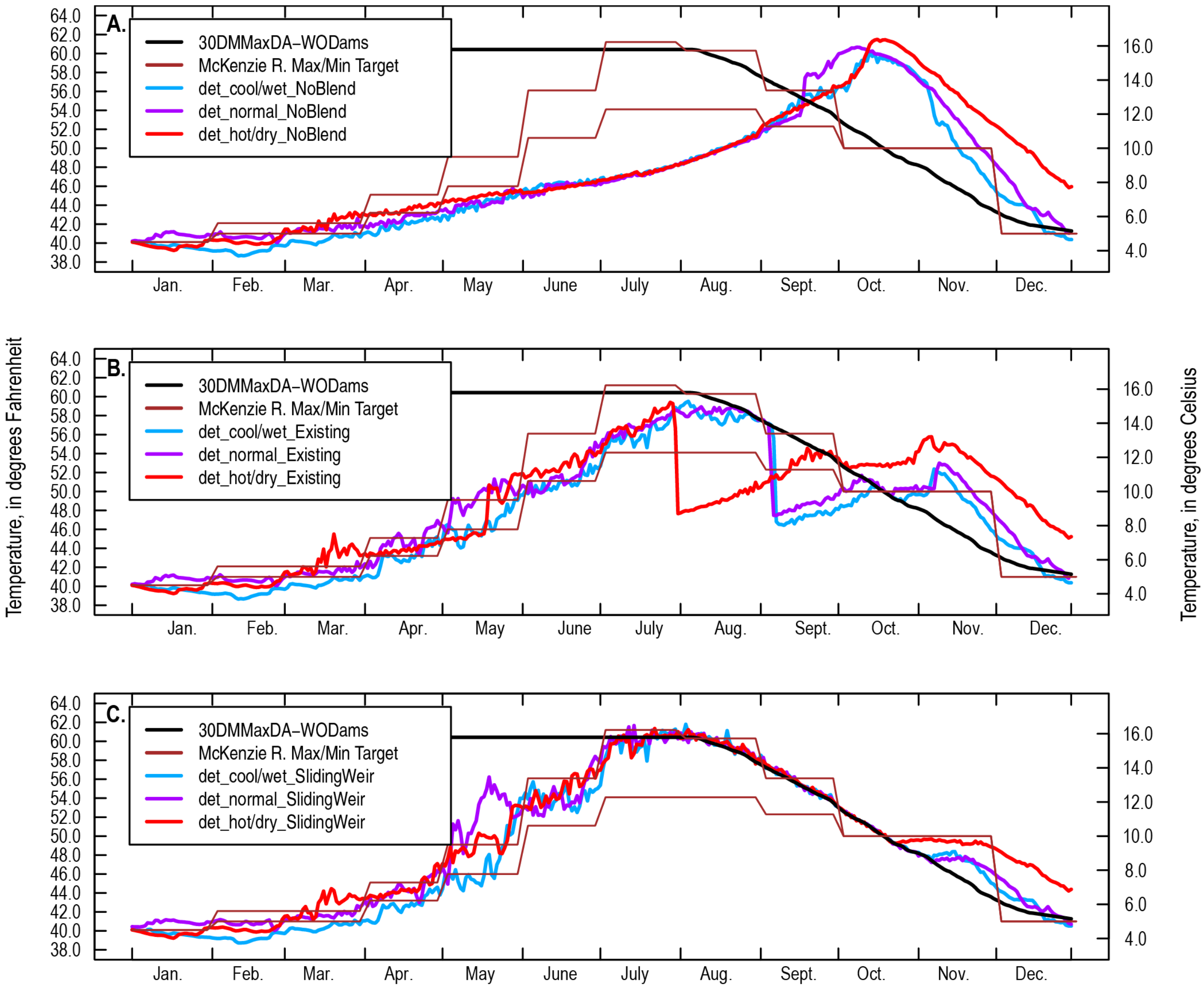

Figure 6. Graphs showing simulated release temperatures at Detroit Dam, Oregon, under three structural scenarios: (A) *NoBlend* (scenarios *c1, n1, h1*), (B) *Existing* (scenarios *c2, n2, h2*), and (C) *SlidingWeir* (scenarios *c3, n3, h3*). 30DMMaxDM-WODams, temperature target used in this study; McKenzie R. Max/Min Target, maximum and minimum temperature target established for the McKenzie River.

By allowing blending between the power penstock releases and either the spillway or upper ROs at Detroit Dam, release temperatures from the *Existing* structural scenarios under *Base* operating conditions were warmer in summer months and cooler in the autumn compared with the *NoBlend* scenarios (figs. 6A and 6B). In this scenario, at least 40 percent of the total release was reserved for power production at all times (MINFRAC = 0.4 for the penstocks, table 4), and other releases (called “spill” in this report regardless of whether it was over the spillway or through the upper RO) ranged from 0 to 60 percent, as needed to try to meet the release temperature target (fig. 7). As the lake elevation declined below the spillway crest under *Existing* structural scenarios (late July in *h2*; early September in *c2, n2*), the spillway could no longer be used, resulting in an immediate decrease in release temperature from Detroit Dam (fig. 6B). During autumn, all *Existing* scenarios resulted in release temperatures warmer than the temperature target. Because of lower lake elevations in scenario *h2*, spillway usage was limited during the summer and led to the warmest release temperatures during the autumn for *Existing* scenarios.

With the addition of a hypothetical withdrawal near the surface of the lake and a lower weir withdrawal (hypothetically routed through the Detroit Dam power house), release temperatures from *SlidingWeir* structural scenarios under *HighPeak* operational scenarios were warmer from May to mid-September and cooler from mid-October to December compared with *NoBlend* and *Existing* structural scenarios (fig. 6C). Simulated releases primarily were from the hypothetical upper weir during January to mid-July, at which point the temperature target begins decreasing and deeper, cooler water (from the lower weir) was needed to mix with warmer surface water to meet the temperature target (figs. 8A and 8B). Some instances of spill (flow through the spillway or the upper RO, as scheduled) occurred during high inflow events (scenarios *c3, n3*) but seemed to affect the outflow temperatures only minimally (figs. 8C and 6C).

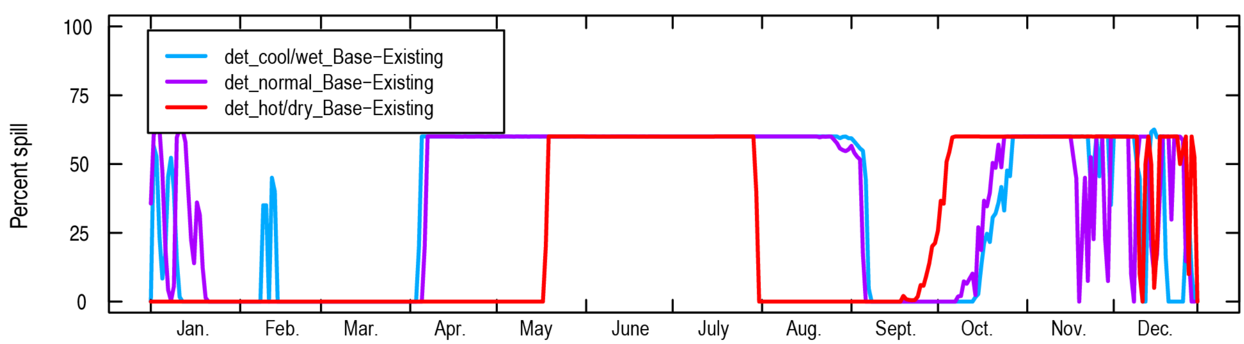

Figure 7. Graph showing simulated percent spill at Detroit Dam, northwestern Oregon, for *Existing* structural scenarios and *Base* operational conditions (scenarios *c2, n2, h2*). Percent spill is the percentage of total flow directed to outlets other than the power penstocks.

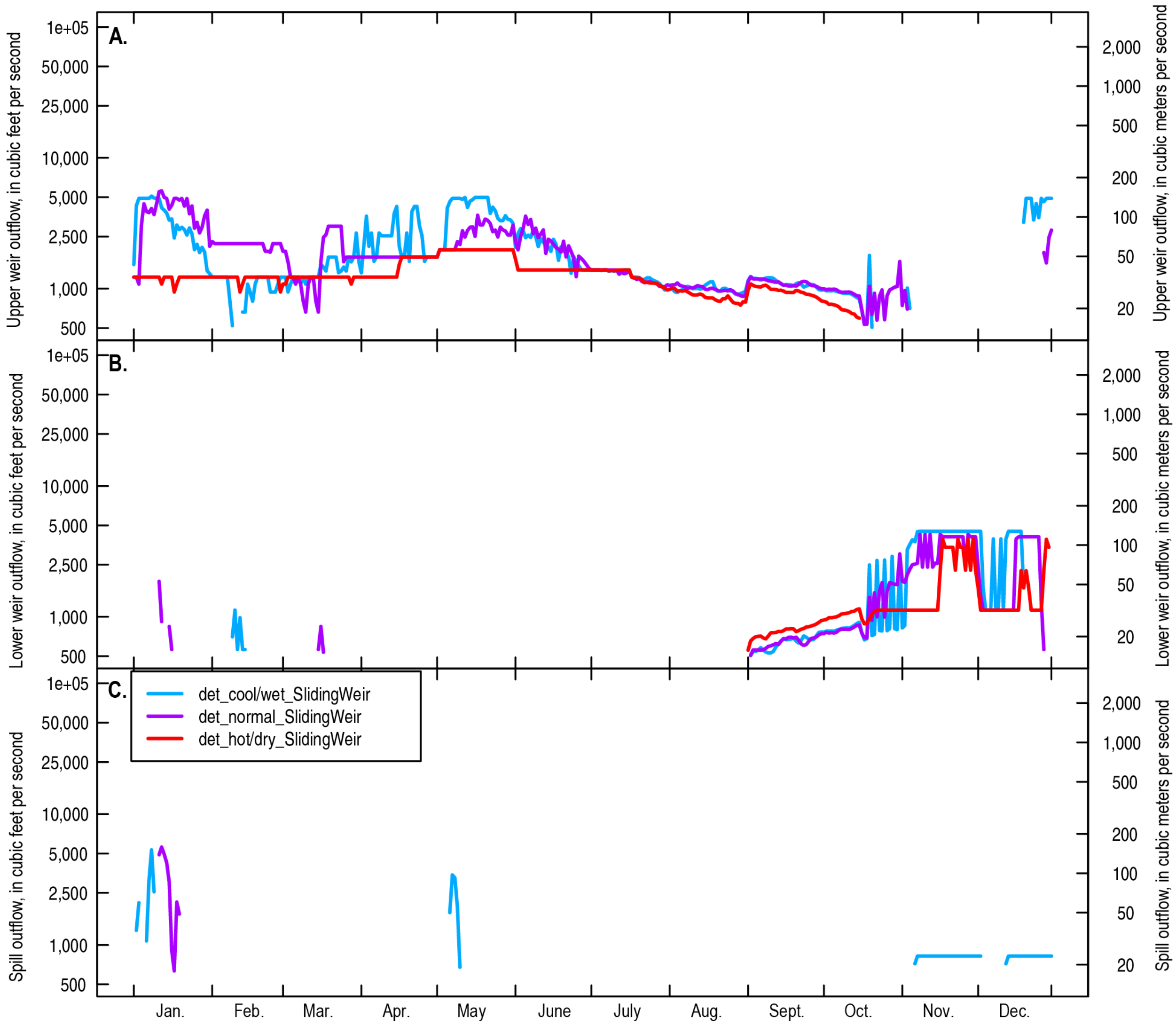

Figure 8. Graphs showing simulated release rates from (A) hypothetical upper weir, (B) hypothetical lower weir, and (C) spill under *SlidingWeir* structural scenarios and *HighPeak* operational conditions (scenarios *c3, n3, h3*) at Detroit Dam, northwestern Oregon. Spill, spillway outflow when lake levels are above spillway crest and flow through upper RO when lake levels are below spillway crest.

Big Cliff Lake Water Balance and Heat Exchange

Short residence times in Big Cliff Lake (about 1 day) led to some difficulty in achieving a water balance that resulted in relatively constant simulated lake elevations (fig. 9). Simulated Big Cliff Lake elevations under the *Base* operational scenarios generally were between 1,180 and 1,200 ft except for a few days under the *normal* and *cool/wet* environmental scenarios (fig. 9A). Under *HighPeak* operational scenarios, the simulated lake levels were within the normal operating range (1,182.0– 1,205.8 ft) (fig. 9B).

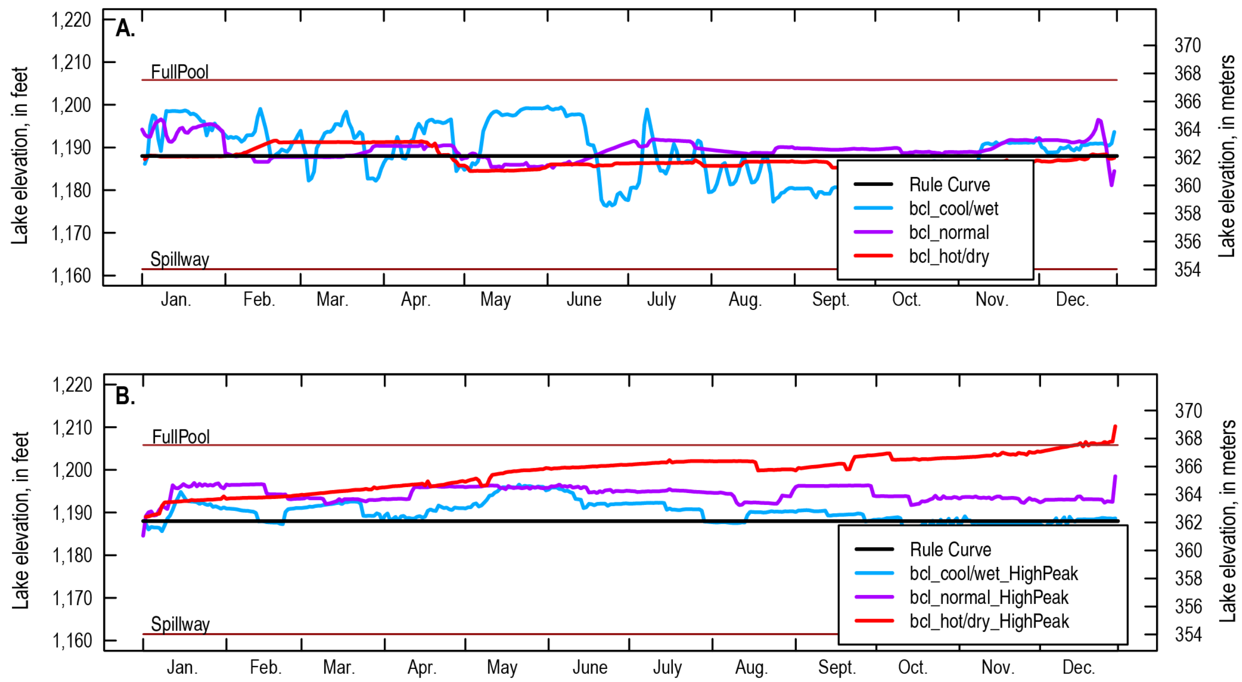

Figure 9. Graphs showing simulated lake elevations and rule curve from (A) *Base and (*B*) HighPeak* operational scenarios under three environmental scenarios (*cool/wet*, *normal*, and *hot/dry*) at Big Cliff Dam, northwestern Oregon.

Heat exchange within Big Cliff Lake depended largely on the difference between Detroit Dam release temperatures and the seasonal ambient air temperature. The largest changes occurred during the summer months in the *NoBlend* scenarios, in which unseasonably cool water released from Detroit Dam led to as much as 1 °C in warming from Detroit Dam to Big Cliff Dam in late July (fig. 10A). Likewise, during the autumn (September–December), unseasonably warm water was released from Detroit Dam in the *NoBlend* scenarios and that water cooled as much as about 0.6 °C in Big Cliff Lake (fig. 10A). The greatest warming in Big Cliff Lake during the *Existing* structural scenarios occurred in late July or early September as a result of Detroit Lake levels declining below the spillway crest elevation, which resulted in the only available outlets at Detroit Dam (power penstocks and upper RO) releasing unseasonably cool water (fig. 10B). Relatively less heat exchange was seen in Big Cliff Lake under the *SlidingWeir* scenarios because the release temperatures from Detroit Dam already had a more natural seasonal profile, closer to equilibrium with expected temperatures (fig. 10C).

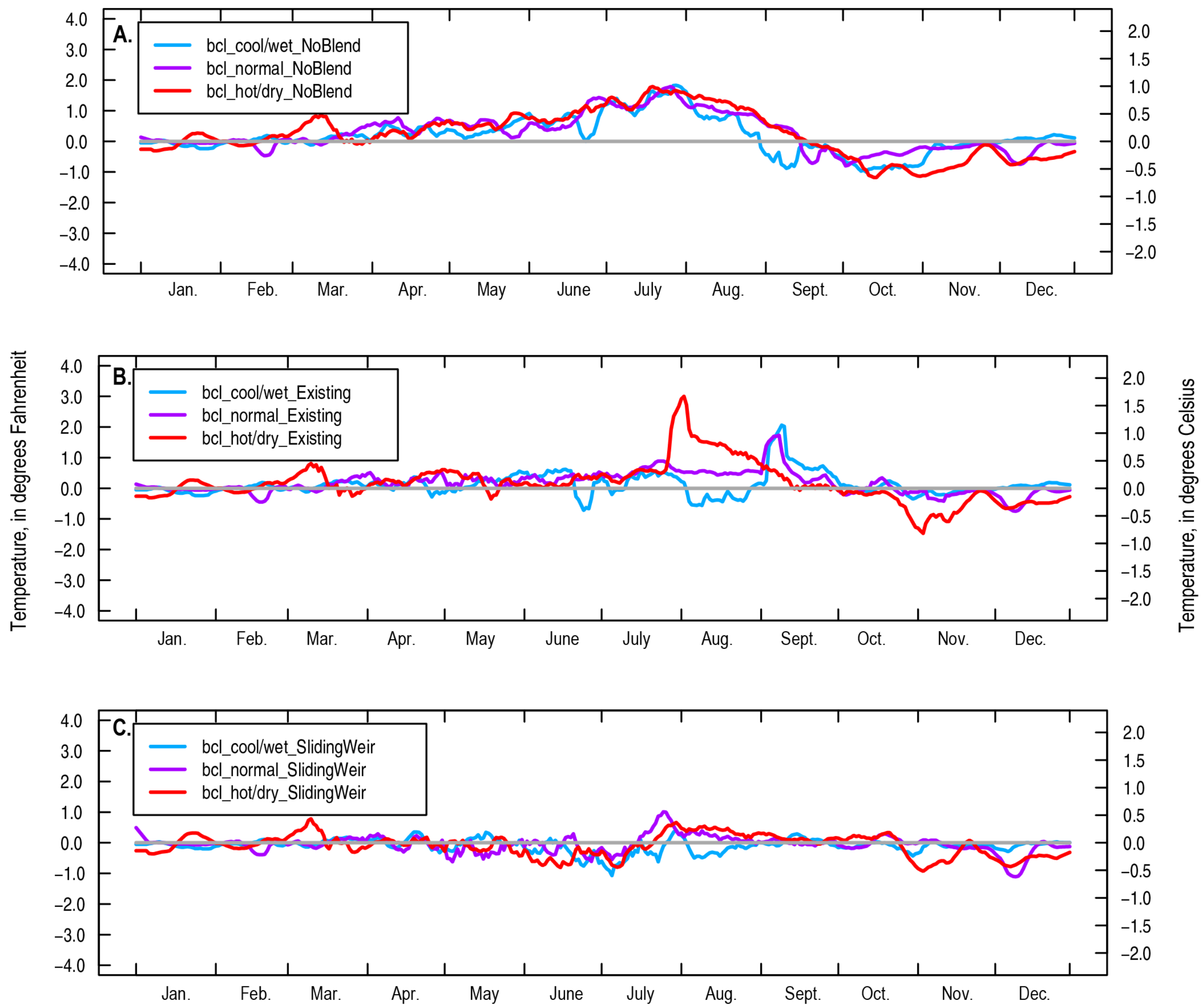

Figure 10. Graphs showing simulated temperature difference between releases from Big Cliff and Detroit Dams, northwestern Oregon, under three structural scenarios: (A) *NoBlend* (scenarios *c1, n1, h1*), (B) *Existing* (scenarios *c2, n2, h2*), and (C) *SlidingWeir* (scenarios *c3, n3, h3*).

Effects Downstream of Detroit-Big Cliff Dams

Temperatures in the North Santiam River downstream of the Detroit-Big Cliff Dam complex were simulated using the North Santiam River HEC-RAS model and assessed at Mehama (USGS station 14183000) and Greens Bridge (USGS station 14184100) (RM 38.7 and 14.6, respectively). Along with results from the structural scenarios, a set of *WithoutDams* scenarios using the without-dams temperatures estimated at the Big Cliff Dam site also were run through the North Santiam River model to provide a comparison for a more natural seasonal temperature pattern.

Downstream Temperatures

About 19.39 river miles downstream of Big Cliff Dam at the USGS streamflow-gaging station at Mehama, the temperature effects occurring immediately downstream of the dams are still apparent, but somewhat affected by river dynamics and heat gains and losses during the travel time to that location (fig. 11). Similar to results downstream of Detroit Dam, *NoBlend* scenario results are cooler during June–August and warmer during October–December compared to results from without-dams scenarios run with the three environmental scenario conditions (fig. 11A). *Existing* scenario temperatures at Mehama are similar to the simulated without-dams temperatures (fig. 11B) until the spillway at Detroit Dam becomes unavailable and additional cool, deep lake water from the power outlets must be released instead (late July in *hot/dry* and early September in *cool/wet*, *normal*). *SlidingWeir* scenario results are largely within the range of the simulated *WithoutDams* temperatures (under *cool/wet, normal,* and *hot/dry* environmental conditions) for most of the year, aside from exceedances (primarily *h2* scenario) in late September through December and some short periods during the spring.

Farther downstream at Greens Bridge, more day-to-day variation in stream temperature was evident as the river had more time to exchange heat with its surroundings and come closer to a dynamic temperature equilibrium as the water traveled about 43.5 river miles downstream of Big Cliff Dam (fig. 12**)**. Relative to *WithoutDams* temperatures, many of the same patterns that occurred at Mehama also were apparent at Greens Bridge. While all temperatures were simulated to increase as the water moved farther downstream in mid-summer, the *WithoutDams* temperatures increased to a greater extent than those in the *NoBlend*, *Existing*, and *SlidingWeir* scenarios from July through mid-October (comparing figs. 11 and 12). The difference is due to the higher streamflows in mid- to late-summer for the scenarios that included the dams, in order to fulfill minimum instream flow and irrigation requirements. The greater mass associated with higher discharge rates was less affected by instream heating, and the higher velocities associated with the higher flows allowed less time for heat exchange, compared to *WithoutDams* flows, leading to cooler temperatures relative to those produced in the *WithoutDams* scenarios. Later in November, temperatures from the *NoBlend* and *Existing* scenarios were similar at both Mehama and Greens Bridge, while December temperatures showed similarities among all three structural scenarios (*NoBlend*, *Existing*, and *SlidingWeir*) at these two stations.

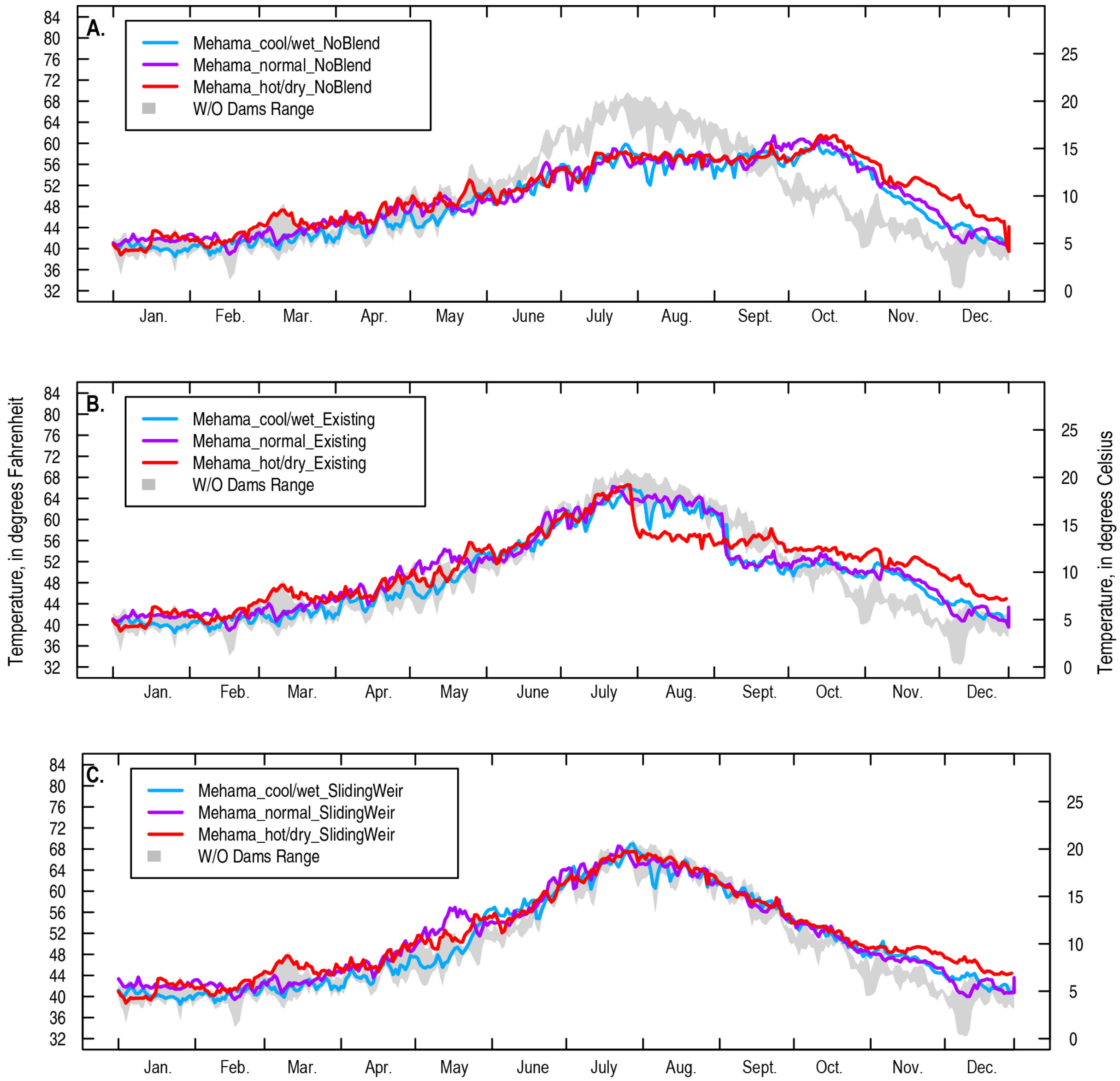

Figure 11. Graphs showing simulated temperatures at Mehama (RM 38.7) on the North Santiam River, northwestern Oregon, under three environmental scenarios (*cool/wet*, *normal*, and *hot/dry*) and three structural scenarios: (A) *NoBlend*, (B) *Existing*, and (C) *SlidingWeir*. The range of the simulated *WithoutDams* scenario temperatures is shaded.

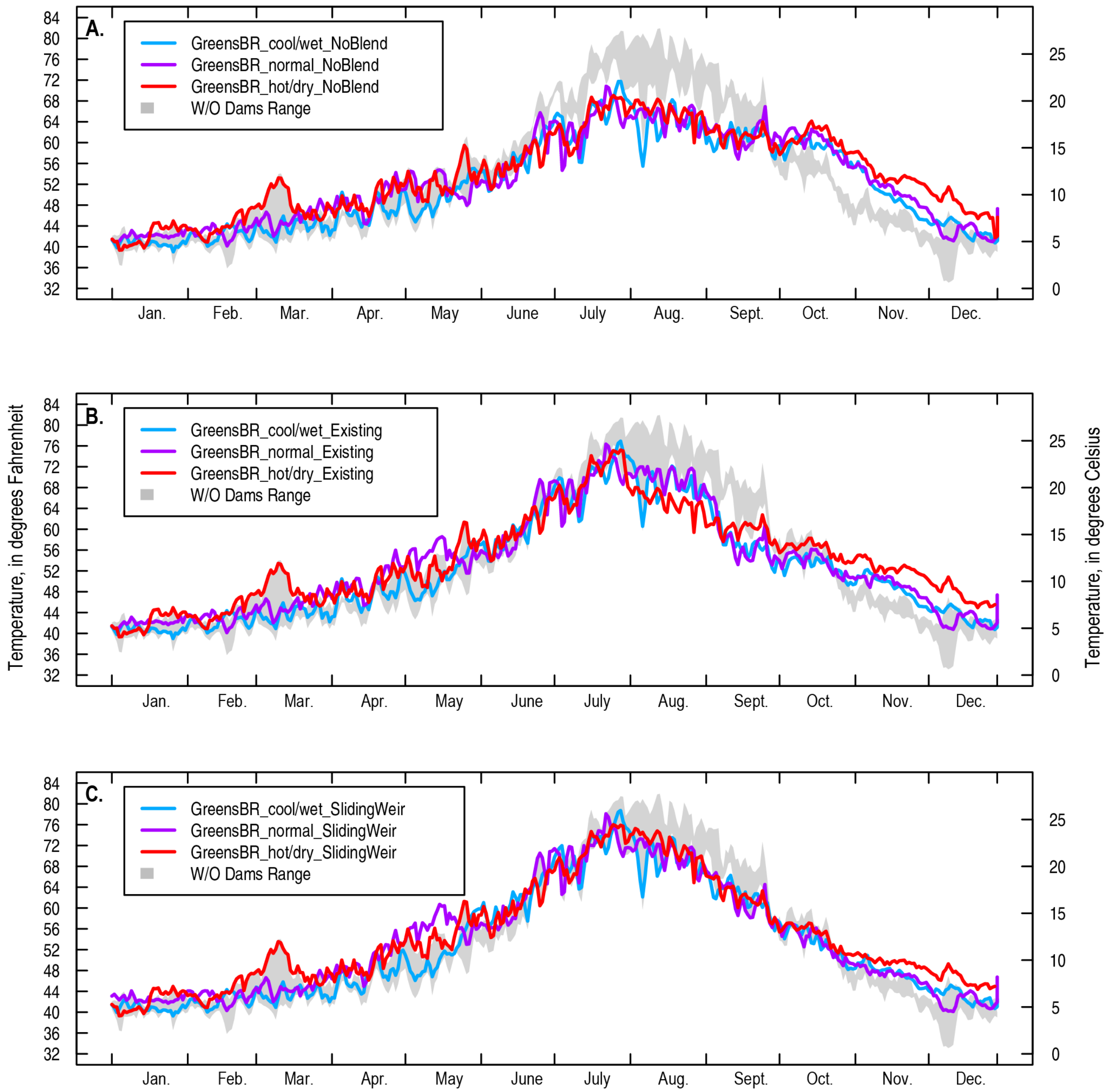

Figure 12. Graphs showing simulated temperatures at Greens Bridge (RM 14.6) on the North Santiam River, northwestern Oregon, under three environmental scenarios (*cool/wet*, *normal*, and *hot/dry*) and three structural scenarios: (A) *NoBlend*, (B) *Existing*, and (C) *SlidingWeir*. The range of the simulated *WithoutDams* scenario temperatures is shaded.

These temperature simulations can be used to estimate how much warmer or cooler the river might be under various structural and operational scenarios, relative to what might have occurred if the dams continued to be operated without any blending, maximizing the power production at Detroit Dam in the manner of operation prior to 2007. Computing those temperature differences reveals that the changes are large, even as far downstream as Greens Bridge (fig. 13), and range as high as 6 °C or more of warming in July and August and a similar amount of cooling in October. This is a significant downstream effect, and likely would trigger a meaningful biological response with regard to the timing of anadromous fish migration and spawning.

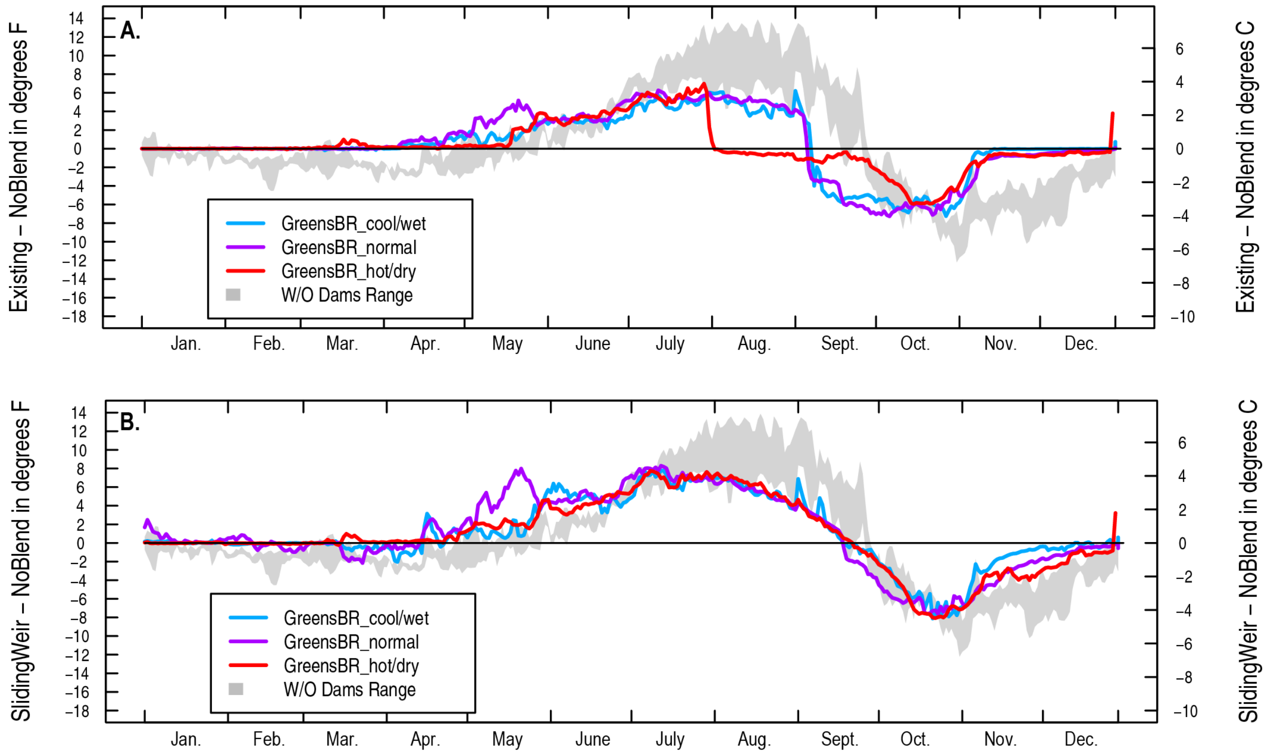

Figure 13. Graphs showing simulated heating or cooling effect of the (A) *Existing* and (B) *SlidingWeir* structural scenario results relative to the temperatures simulated in the *NoBlend* structural scenarios at Greens Bridge (RM 14.6) on the North Santiam River, northwestern Oregon, under three environmental scenarios (*cool/wet*, *normal*, and *hot/dry*). The range of the simulated *WithoutDams* scenario relative to the *NoBlend* structural scenario temperatures is shaded.

Potential Biological Effects

Salmon have adapted the timing of their upstream migration and spawning relative to their home stream (Knudsen and McDonald, 1999). The date at which spawning occurs has been evolutionarily linked to the temperature in which egg incubation has occurred (Brannan, 1987). Because salmon have adapted to temperature regimes that were in existence prior to the construction of dams, the without-dam temperature estimates are a useful baseline from which to measure the relative success of scenarios in this report to restore a more-natural seasonal temperature pattern.

Estimated Emergence Dates

An accumulated thermal unit (ATU) is a calculated quantity used to estimate the date on which spring Chinook salmon first emerge from their eggs (U.S. Army Corps of Engineers, 2012). This type of calculation was used to compare the potential emergence dates among the scenarios during spring and autumn spawning periods. The ATU calculation in this report is the cumulative sum of the daily average temperature (°F) exceeding 32 °F beginning on September 20 and May 1 to estimate the timing of spring Chinook and winter Steelhead egg emergence, respectively. For winter Steelhead, the estimated emergence day is derived as the date when ATU values reach 1,000–1,100 °F/day in early summer (U.S. Army Corps of Engineers, 2009). In contrast, spring Chinook are known to emerge at an ATU between 1,650 and 1,850 °F/day in autumn (based on observed egg emergences at the Oregon Department of Fish and Wildlife Willamette Hatchery in Oakridge, Oregon [U.S. Army Corps of Engineers, 2012]).

Near Big Cliff Dam, estimated winter steelhead emergence timing during the spring for *SlidingWeir, Existing,* and *NoBlend* scenarios was before, within, and after the range of emergence timing computed for the *WithoutDams* scenarios, respectively (fig. 14). While earlier emergence of winter steelhead during spring can allow more time for fry to feed during summer (should enough food exist) and develop before over-wintering, emergence timing within the bounds of the *WithoutDams* scenarios could indicate that the effect of the dams is minimal for *Existing* scenarios. Relatively early emergence times from the *SlidingWeir* scenarios during the spring reflects the ability of these hypothetical structures to release surface water from Detroit Lake that is warmer than that produced in the *WithoutDams* scenarios. This is likely a result of using a maximum value (15.9 °C) for the temperature target from January through July; the results might have been closer to the range of the results from the *WithoutDams* scenarios if the temperature target were to reflect historical without-dams conditions year round. Moving downstream of Big Cliff Dam to Mehama and Greens Bridge, the diminished effects of the dams with increasing downstream distance led to earlier winter Steelhead emergence estimates and a smaller difference between emergence timing under all four scenarios (fig. 14). For example, at Big Cliff Dam the range of emergence timing from *SlidingWeir* and *NoBlend* scenarios was greater than the difference at Greens Bridge (figs. 14A and 14C).

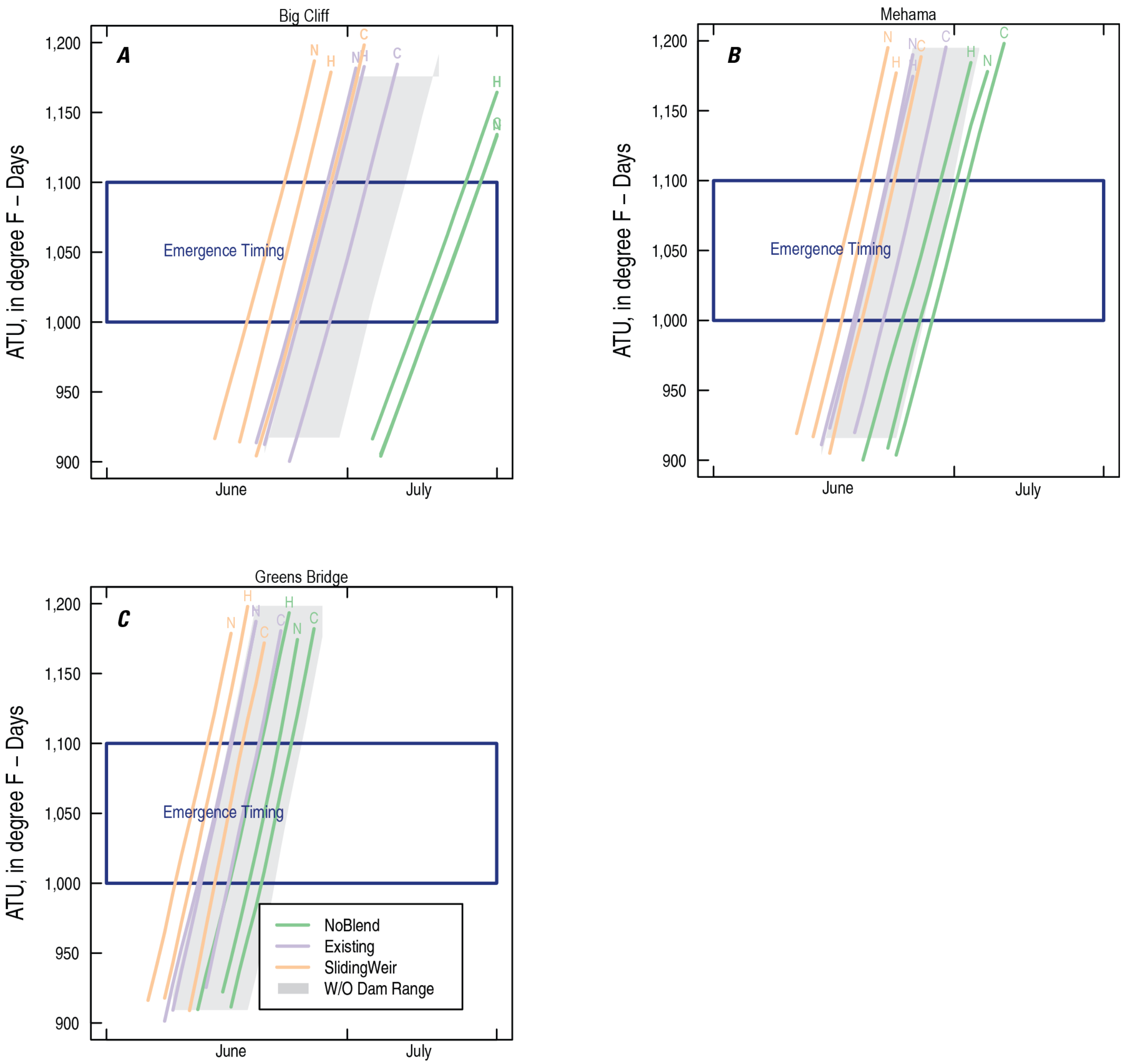

Figure 14. Mean accumulated thermal units (ATUs) starting May 1 from *Existing*, *NoBlend*, and *SlidingWeir* structural scenarios at (A) Big Cliff Dam, (B), Mehama, and (C), Greens Bridge sites on the North Santiam River, northwestern Oregon. ATU range is shown in gray for scenarios. Colored “C”, “N”, and ”H” next to lines indicate *cool/wet*, *normal*, and *hot/dry* environmental scenarios.

During autumn, mean estimated spring Chinook emergence times were more variable among scenarios than winter steelhead emergence times. Estimated emergence under *Existing* and *SlidingWeir* scenarios for *normal* and *cool/wet* environmental conditions were similar and closest to the *WithoutDams* range (fig. 15). A larger divergence among structural scenarios was evident and persistent from Big Cliff Dam to Greens Bridge under the *hot/dry* environmental scenarios compared with the *normal* and *cool/wet* (labeled "H", "N", and "C" respectively, fig. 14). The average emergence days beginning September 20 for each scenario at four locations (Detroit Dam, Big Cliff Dam, Mehama, and Greens Bridge) are shown in table 6. All scenarios except for *NoBlend* resulted in earlier emergence days moving downstream of Big Cliff Dam to Mehama and Greens Bridge (table 6). This is a result of North Santiam River temperatures generally warming from Big Cliff Dam to Greens Bridge during the autumn under all scenarios except *NoBlend*.

Table 6. Calculated average emergence day for the *cool/wet*, *normal*, and *hot/dry* environmental forcings at four locations from the Detroit Lake, Big Cliff Lake, and North Santiam River models, northwestern Oregon.

[Emergence days are based on the day at which the accumulated thermal units (ATUs) for simulated temperatures reached 1,750 °F-day. ATU values were calculated as the cumulative sum of the average daily water temperature above 32 °F from September 20 through December 31. Dates in January and February were estimated based on model results from earlier in the year of each environmental scenario]

Scenario identifier	Scenario description	Scenario type	Average spring Chinook emergence day			
			Detroit Dam (RM 60.9)	Big Cliff Dam (RM 58)	Mehama (RM 38.7)	Greens Bridge (RM 14.6)
c1, n1, h1	*NoBlend*	operational	Dec. 2	Dec. 5	Dec. 7	Dec. 1
c2, n2, h2	*Existing*	operational	Jan. 6	Jan. 8	Jan. 3	Dec. 23
c3, n3, h3	*SlidingWeir*	structural	Jan. 13	Jan. 17	Jan. 9	Dec. 27
--	*WithoutDams*[1]	--	Mar. 30	Mar. 30	Feb. 18	Jan. 11

[1]Without-dams scenario estimated at Big Cliff Dam, then simulated in North Santiam River model.

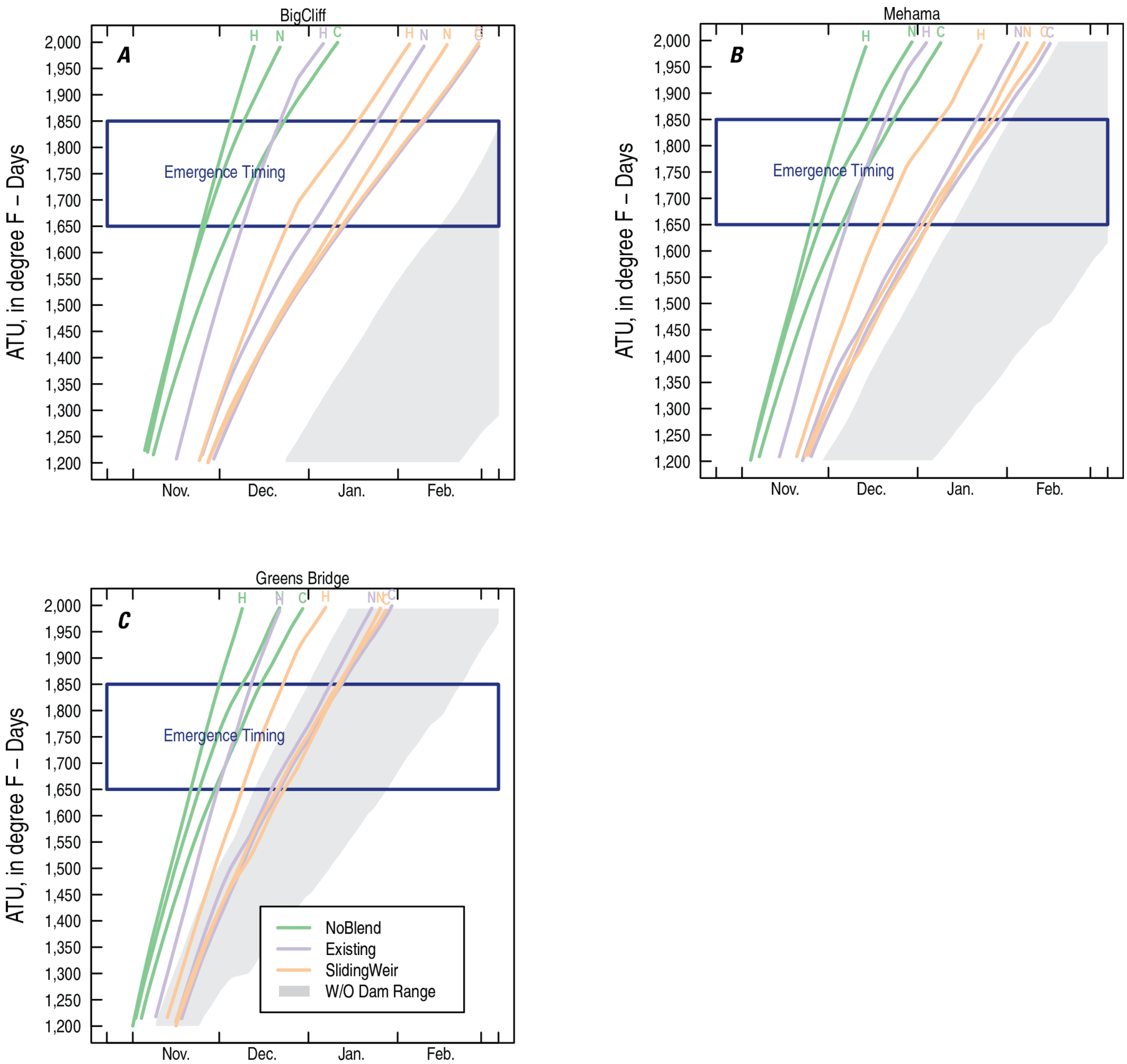

Figure 15. Graphs showing mean accumulated thermal units (ATUs) starting September 20 from *Existing*, *NoBlend*, and *SlidingWeir* structural scenarios at (A) Big Cliff Dam, (B) Mehama, and (C) Greens Bridge sites on the North Santiam River, northwestern Oregon. ATU range is shown in gray for *WithoutDams* scenarios. Colored “C”, “N”, and ”H” next to lines indicate *cool/wet*, *normal*, and *hot/dry* environmental scenarios.

Summary

The circulation and water temperature in Detroit Lake were simulated with a CE-QUAL-W2 model to assess the potential for a hypothetical sliding weir at Detroit Dam (*SlidingWeir* scenario) to release more natural, without-dam temperatures year round. A temperature target based on long-term without-dam temperature estimates was developed and used to guide the CE-QUAL-W2 temperature model in mixing releases among the user-defined outlets at Detroit Dam. The hypothetical sliding weir (named “upper weir”) was assumed to be internally connected to the power penstocks within Detroit Dam so that blending among warmer and cooler outlets to meet the temperature target did not infringe on power production. *SlidingWeir* scenarios typically released warm surface water during spring and summer, while saving cooler, deeper hypolimnetic water for release later during autumn. Near Detroit Dam, *SlidingWeir* scenarios resulted in temperatures within the range of without-dams scenario results for most months of the year until about November. At that time of year, the heat captured by the lake during the warmer summer months still has a residual effect at all depths of the lake, leading to dam releases that are warmer than inflowing tributaries to Detroit Lake.

Between Detroit and Big Cliff Dams, a comparison of scenarios revealed that heat exchange within Big Cliff Lake generally increased as Detroit Dam release temperatures departed from seasonal ambient air temperature or without-dam temperature estimates. Scenarios in which blending between warmer and cooler outlets occurred (*Existing*, *SlidingWeir* scenarios) resulted in less heating within Big Cliff Lake in summer than scenarios in which Detroit Dam releases were cooler in summer and solely from the power penstocks (*NoBlend* scenarios).

Downstream of the dams, the minimum release rates imposed at Detroit Dam during late summer and early autumn exceeded the unregulated without-dams flow estimates. This larger mass of water exchanged less heat with its surroundings as it moved downstream of the dams, as compared to results from the *WithoutDams* scenarios. For *SlidingWeir* simulations, this pattern led to temperatures near the lower minimum of the *WithoutDams* temperature range downstream (46.3 river miles) at Greens Bridge during July– September. Later in November and December, *SlidingWeir* scenario results were closer to the maximum *WithoutDams* temperatures at Greens Bridge than upstream at Mehama. Among all Detroit Dam scenarios, the effects during November and December of Detroit Dam were persistent, but less pronounced at Greens Bridge than at Mehama when compared to *WithoutDams* scenarios. Simulations that included the blending of warm and cool water from different outlets at Detroit Dam (*Existing*, *SlidingWeir* scenarios) led to less day-to-day temperature variation than *WithoutDams* scenarios as far downstream as Greens Bridge.

The calculation of estimated egg-emergence dates helped to evaluate the cumulative effect of temperature during winter steelhead and spring Chinook incubation periods and served to compare scenario results during these critical life history stages. As with water temperatures, emergence dates were more divergent among scenarios near Big Cliff Dam than downstream at Mehama and Greens Bridge. For example, the average spring Chinook emergence day for *SlidingWeir* scenarios was 9 days later than it was for *Existing* scenarios at Big Cliff Dam, but only 4 days later than it was for *Existing* scenarios downstream at Greens Bridge. The difference between spring Chinook emergence estimates for *SlidingWeir* and *Existing* scenario was greater under *hot/dry* scenarios, most likely because of lower Detroit lake levels (lower lake volume). This result shows that the benefit of blending operations can be more extreme. Similarly, the difference between Detroit Dam scenarios and the *WithoutDams* scenarios estimated emergence days decreased from Big Cliff Dam to Greens Bridge.

Simulations of a hypothetical sliding weir (connected internally within the dam to the power penstocks) at Detroit Dam resulted in near-dam temperatures that closely matched without-dam temperature estimates during January through October, from Big Cliff Dam to Greens Bridge on the North Santiam River. This hypothetical structure improved outflow temperature control from Detroit Dam while meeting minimum dry-season release rates and lake levels specified by the current rule curve specified for Detroit Lake. Despite this inclusion of a hypothetical sliding weir at Detroit Dam, temperatures exceeded without-dams temperatures during November and December. These exceedances likely represent the residual thermal effect of the mere existence of Detroit Lake. Further optimization of temperature management at Detroit Lake/Dam might focus towards the balance of release rates (streamflow), lake elevation, and downstream water temperature at specific spawning grounds or habitat zones downstream of Big Cliff Dam throughout the year, especially during late summer and autumn.

Acknowledgments

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