

Coupled in-reservoir and downstream water-temperature responses to the deep drawdown of a large reservoir, and tradeoffs for fisheries management

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Abstract

Across the Pacific Northwest and other regions, the construction and operation of large dams has provided numerous societal benefits but has also fundamentally altered present-day river networks by blocking fish passage and altering streamflows and thermal regimes. Increasingly, evolving management directives require dam operations far outside of historical operational regimes to achieve new objectives utilizing existing dam infrastructure. In the Willamette River Basin of northwestern Oregon where the U.S. Army Corps of Engineers operates 13 dams comprising the Willamette Valley System, deep reservoir drawdowns of over 30.5 m (100 ft) below typical operational lake levels have been implemented at

multiple sites as a strategy to facilitate downstream passage of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Because reservoir thermal conditions, dam operations, and downstream release temperatures are closely coupled, deep drawdowns must be strategically planned to avoid releasing potentially harmful warm water to downstream reaches where adult salmon spawn. To better understand and quantify these thermal tradeoffs and evaluate mitigation strategies, we analyzed water temperatures upstream and downstream from Green Peter Dam, a high-head dam on the Middle Santiam River in the South Santiam River Basin in northwestern Oregon. We compared release temperatures and reservoir conditions from three deep drawdown years (2023-2025) with historical temperature data and simulated three additional drawdown timing scenarios using a two-dimensional hydrodynamic model under consistent hydroclimatic conditions. Deep drawdowns produced cooler mid-summer release temperatures but substantially warmer maximum release temperatures in autumn relative to historical norms. Maximum daily mean release temperatures of 16.9-18.7 °C in autumn exceeded thermal thresholds associated with egg mortality and coincided with the spawning and egg incubation period for spring Chinook salmon. The magnitude of peak release temperatures in autumn depends on several factors such as late summer and autumn meteorological conditions, the degree to which the reservoir fills during spring, summertime dam operations, and the timing of a deep drawdown. To reduce these peak water release temperatures, results showed two critical strategies to be helpful: (1) using dam outlets near the water surface to export excess near-surface heat and minimize its accumulation in late spring and early summer, (2) delaying a deep drawdown until seasonal cooling of the epilimnion releases more of its accumulation of summer-sourced heat to the surrounding environment, thus minimizing the downstream export of that epilimnetic heat as the drawdown pulls the thermocline down to the level of dam outlets. Implementing these strategies effectively depends on real-time monitoring of reservoir thermal structure, which could inform outlet and drawdown timing decisions. This case study illustrates the utility of process-based modeling for characterizing the close coupling between reservoir thermal conditions, dam operations, and downstream release temperatures. This case study also highlights the importance of managing the thermal tradeoffs of different dam operations from a systems and life-cycle perspective,

50 wherein complementary monitoring and modeling strategies are used to rigorously evaluate those
51 tradeoffs to inform highly consequential dam management operations.

52

53 Introduction

54 The health of Pacific salmon (*Oncorhynchus* sp.) populations depends on the availability of appropriate
55 habitat and the ability to migrate between the ocean and river corridors supporting different life stages.
56 Across the Pacific Northwest and other regions, the widespread proliferation of large (>15 m;
57 International Conference on Large Dams, 2011) dams during the 20th century fundamentally altered
58 downstream river habitats and the ability of migrating salmon populations to access spawning habitats
59 (Collier et al., 1996; Daniels and Danner, 2020).

60 Streamflows in the Willamette River Basin of northwestern Oregon are regulated by 19 large (>15 m)
61 dams, 13 of which comprise the U.S. Army Corps of Engineers Willamette Valley System (WVS; Figure
62 1). WVS dams historically and presently block passage for adult salmon migrating upstream and for
63 juveniles migrating downstream to the ocean. In addition, WVS dams have fundamentally altered the
64 streamflow and thermal regimes of downstream river reaches, with wide-ranging implications for
65 temperature-sensitive fishes that depend on specific thermal conditions during critical life stages (Collier
66 et al., 1996; Daniels and Danner, 2020; Keefer et al., 2015, 2010; McCullough, 1999; National Marine
67 Fisheries Service, 2008; Richter and Kolmes, 2005). These and other stressors have contributed to the
68 listing of native Upper Willamette River (UWR) spring Chinook salmon (*Oncorhynchus tshawytscha*) and
69 Upper Willamette River winter steelhead (*O. mykiss*) as threatened under the Endangered Species Act
70 (ESA) of 1973 (Public Law 93–205, 87 Stat. 884, as amended; National Marine Fisheries Service, 1999a,
71 1999b, 2008, 2024).

72 WVS dams are managed for multiple purposes including flood-risk minimization, hydropower
73 generation, municipal and agricultural water supply, recreation, and fish and wildlife. Although upstream
74 passage for adults has been largely implemented through trap and haul programs, effective downstream
75 juvenile passage options remain limited. Downstream passage routes depend on the specific configuration
76 and availability of outlets at individual dams, which shift throughout the year as reservoir elevations

fluctuate with management operations (Hansen et al., 2017). Passage through turbines, may sometimes be the only available route but can cause substantial mortality (Keefer et al., 2013; Algera et al., 2020).

Structural solutions such as forebay collectors have been implemented at some dams, but are costly and often perform poorly at large multi-purpose reservoirs that may extend tens of kilometers with annual pool level fluctuations that can exceed 30 meters (Hansen et al., 2017; Kock et al., 2019).

Deep reservoir drawdowns (henceforth “deep drawdowns”) utilize existing dam infrastructure to provide an alternative strategy for downstream passage by lowering reservoir pool levels below typical operating elevations to shrink the pooled area that juveniles must navigate and enable access to low-elevation dam outlets that are safer for their downstream passage (Kock et al., 2019; Murphy et al., 2019). Deep drawdowns to facilitate downstream passage of juvenile salmon have been implemented or proposed at several WVS dams, including Green Peter Dam, Fall Creek Dam, Lookout Point Dam, Cougar Dam, and Detroit Dam (National Marine Fisheries Service, 2024).

The first deep drawdown to facilitate downstream passage of juvenile salmon at Green Peter Dam was implemented in the summer and autumn of 2023 and resulted in water releases to the South Santiam River that were well outside of the range of historical temperatures recorded since 2001, the approximate year when management for the ESA listing of salmon species began (National Marine Fisheries Service, 2008). Stream temperatures well above 12 °C during September and October of 2023 coincided with spawning by adult Chinook salmon immediately downstream of Foster Dam (Martin et al., 2017; U.S. Geological Survey, 2026).

The thermal results of the deep drawdown operation during autumn of 2023 at Green Peter Dam highlight the inherent tensions among different dam management operations, whereby operations to improve conditions for one life stage of salmon may necessarily or unintentionally adversely affect another life stage. To facilitate rigorous evaluation of these tradeoffs and inform decision making, the effects of potential dam operations must be understood and managed from a systems and life-cycle perspective,

wherein the close coupling between reservoir thermal conditions, dam operations, downstream release temperatures, and salmon life stages are rigorously evaluated.

This study uses a combination of observed data analysis and process-based modeling to 1) describe coupled interactions between reservoir thermal conditions, dam operations, and water release temperatures at Green Peter Lake, 2) evaluate the extent to which drawdown operations contribute to potentially adverse thermal conditions for spring Chinook salmon egg incubation downstream, and 3) demonstrate how changes to drawdown timing and other management actions can reduce or mitigate warm autumn release temperatures and minimize potentially harmful conditions for fish downstream.

Background

Study area

The South Santiam River is a major tributary to the Santiam and Willamette Rivers, draining approximately 2,700 km² (Calculated in StreamStats; Ries et al., 2017) Within the basin, Green Peter Dam (99.7 m high) impounds the Middle Santiam River and approximately 5.5 miles downstream, Foster Dam (38.4 m high) impounds the South Santiam River below its confluence with the Middle Santiam River (Figure 1A; Stratton Garvin et al., 2023a; U.S. Geological Survey, 2023). Both dams have multiple outlets at different elevations serving various purposes (Figure 1B for Green Peter Dam; Sullivan and Rounds, 2021). Chinook salmon, winter steelhead, and other native fish use the South Santiam River Basin for various life stages (Schroeder et al., 2016). Upper Willamette River spring Chinook salmon migrate to the South Santiam River in late spring and early summer, hold in deep pools during summer months, and spawn in autumn. Historically, spawning occurred in the Middle Santiam River, Quartzville Creek, and other tributaries upstream of Green Peter Dam as well as in the South Santiam River upstream and downstream of Foster Dam (O'Malley et al., 2024).

Green Peter Dam was completed in 1968 with a downstream migrant facility, which was later decommissioned due to declining fish recruitment attributed to reservoir predation (Couch et al., 2026; Wagner et al., 1973). Outplanting of Chinook salmon above the dam ended in the 1980s at the same time the juvenile migrant facility was decommissioned; hence a naturally producing anadromous Chinook salmon population upstream of Green Peter Dam has been considered largely nonexistent from sometime in the 1970s until outplanting resumed in 2022 (Hansen et al., 2017; R. Piaskowski, USACE, written commun., May 11, 2026). In response to a 2021 court injunction and subsequent 2024 Biological Opinion (BiOp), Chinook salmon were re-introduced to the Middle Santiam River Basin by outplanting of Chinook salmon above Green Peter Dam, and downstream passage was initiated through spillway releases in spring and deep drawdowns in the fall (National Marine Fisheries Service, 2024). Absent spillway releases and deep drawdowns, the main option for downstream juvenile passage was through the power penstock, which is known to produce poor survival rates. The deep drawdown for fish passage through the regulating outlet (RO) at Green Peter Dam requires lowering the reservoir water level approximately 38.1 m below typical minimum pool (National Marine Fisheries Service, 2024).

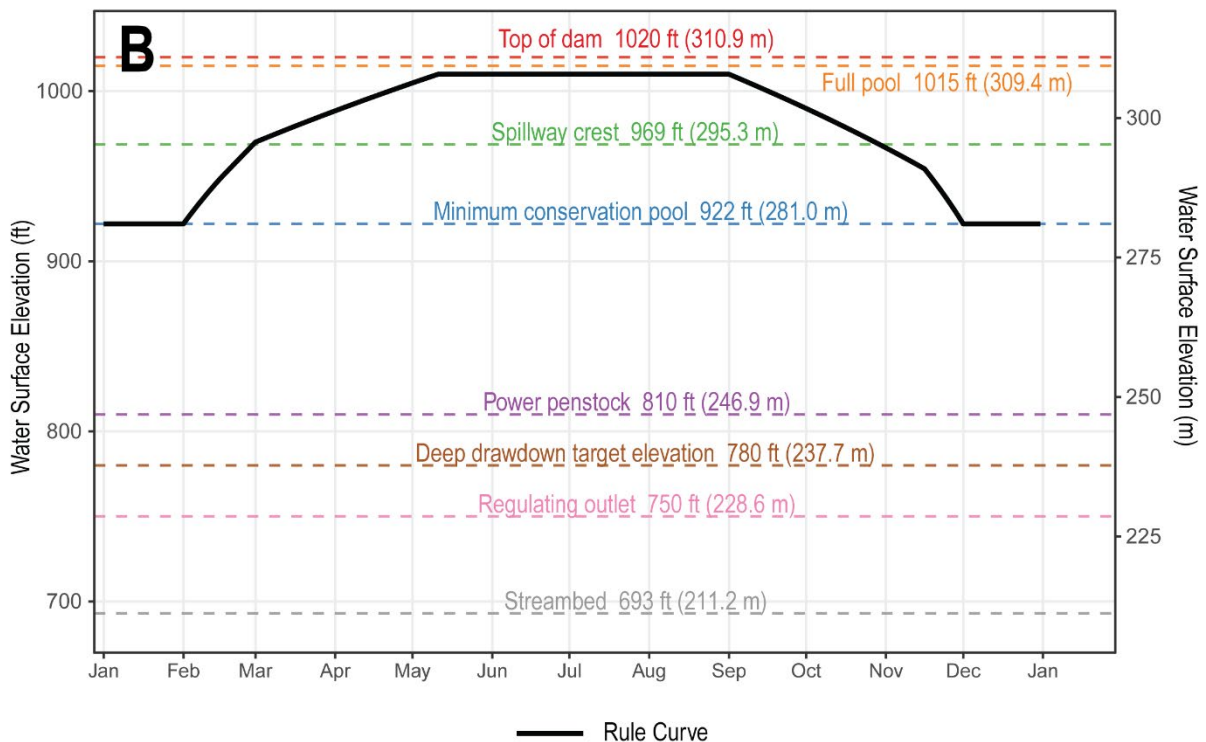
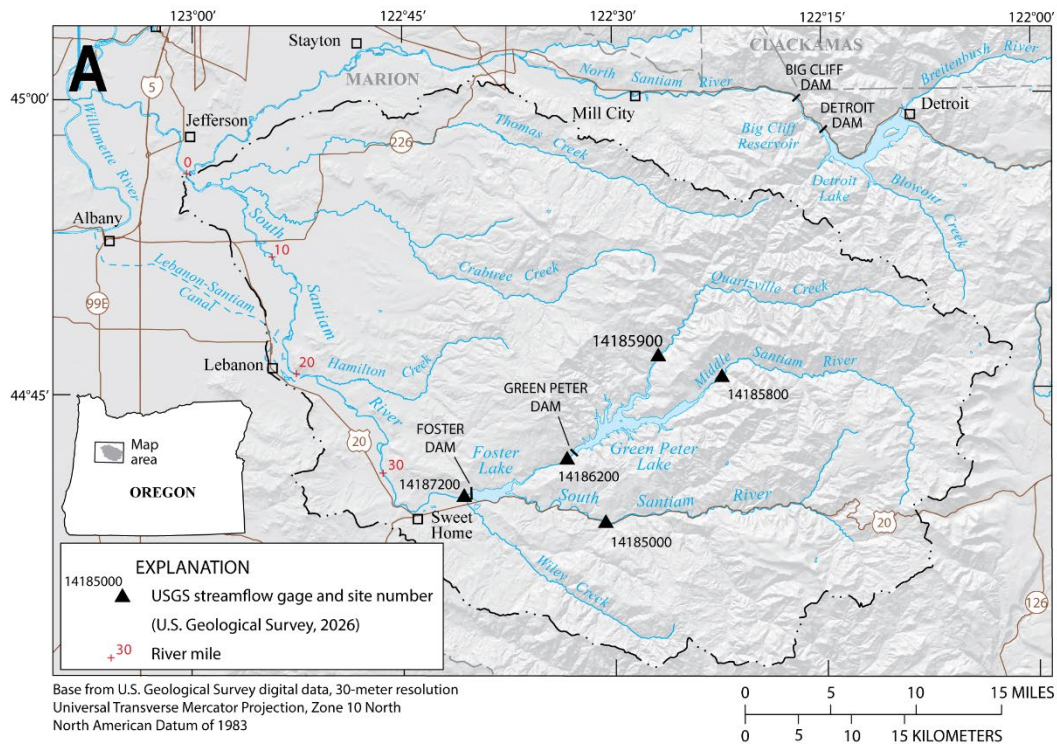
Temperature dynamics in and below reservoirs

Large reservoirs typically develop thermal stratification during spring and summer as solar heating warms surface waters, creating distinct layers that resist vertical mixing due to differences in water density. The warm, less-dense epilimnion is separated from the cooler, denser hypolimnion by the thermocline, a zone of rapid temperature change. Stratification naturally persists through summer and early autumn before cooler air temperatures and reduced solar radiation cause surface waters to cool and stratification to break down. The vertical position of the thermocline is an important factor influencing the temperature of water available at different dam outlet elevations.

Hypolimnetic releases are common at dams with deep outlets; such releases are characterized by dampened amplitudes and altered seasonality of release temperatures (Olden and Naiman, 2010).

Historical operations at Green Peter Dam matched this regime, such that release temperatures were generally cooler during summer and warmer in autumn than undammed conditions (Buccola, 2017; Olden and Naiman, 2010; Rounds, 2010). While temperature dynamics at Foster Dam are more complex, release temperatures from Foster Dam to the South Santiam River downstream are strongly controlled by the temperature of water released by Green Peter Dam (Buccola, 2017; Sullivan and Rounds, 2021). Hence, South Santiam River water temperatures downstream of Foster Dam tend to resemble a similar, but muted pattern compared to temperatures upstream of Foster Lake in the Middle Santiam River below Green Peter Dam. Because Green Peter Dam releases are the primary source of inflow to Foster Lake and exert the dominant control on downstream release temperatures, this study focuses on reservoir thermal dynamics and dam operations at Green Peter Lake.

The temperatures of dam releases from a stratified reservoir depend on the extent of the vertical withdrawal zone—the vertical envelope from which water is pulled through an open dam outlet (Wells, 2019). The thickness of the vertical withdrawal zone is a function of outlet size and geometry, discharge magnitude, and the density gradient in the surrounding part of the water column (Wells, 2019). At low discharges, the vertical withdrawal zone is thin, and water released from an outlet will be similar to the reservoir temperature near the elevation of that outlet. If discharge is sufficiently large, warmer water from the base of the thermocline can be entrained in hypolimnetic dam releases, causing release temperatures to far exceed the reservoir temperature at the outlet elevation.



166

167 Figure 1. A) Study area in the South Santiam River Basin, Oregon. Reproduced from Sullivan and Rounds (2021) and Buccola
168 (2017). B) Summary of relevant pool level and outlet elevations (NGVD29) for Green Peter Dam in the South Santiam River
169 Basin, Oregon adapted from Sullivan and Rounds (2021).

Methods

This analysis relied on a combination of observed temperature data and CE-QUAL-W2 model results to characterize reservoir and release temperature dynamics. Observed data from calendar years with deep drawdown and pre-drawdown years were used to characterize seasonal thermal shifts that result from the two distinct operational regimes. Coupled interactions between reservoir thermal conditions, dam operations, and release temperatures were more thoroughly examined with measured and modeled data from 2016 and 2023. Potential thermal implications for salmon egg incubation during autumn were evaluated by comparing observed data from sites downstream of Green Peter and Foster Dams with thresholds for egg mortality. Finally, the effect of drawdown timing and other management actions on peak autumn release temperatures and potentially harmful conditions for salmonid spawning were evaluated with a combination of three CE-QUAL-W2 model scenarios, each with identical inputs but varied drawdown timing, alongside observed data from 2025. Table 1 summarizes the years and scenarios included in the analysis. Pre-drawdown years (2011, 2015, 2016) were selected to represent a range of hydroclimatic conditions; drawdown years (2023–2025) were included to capture deep drawdown operations. Data sources for observed streamflow, water temperature, and reservoir elevation used in this analysis are described in S1 Appendix.

187 *Table 1. Specific years and model scenarios included in the analysis with a description of the dam operation, and whether*
188 *observed or modeled results were used to assess thermal responses to that scenario. Refer to S1 Appendix for additional*
189 *information about data sources.*

Year	Observed or Modeled	Operation at Green Peter Dam	Observed data source	CE-QUAL-W2 model version used in this study
2011	Observed	2008 Biological Opinion (BiOp) operation (National Marine Fisheries Service, 2008)	Water temperature: USGS site 14186200 (U.S. Geological Survey, 2026); Green Peter Lake elevation: USACE DataQuery 2.0 (U.S. Army Corps of Engineers, 2026)	-
2015	Observed	2008 BiOp operation (National Marine Fisheries Service, 2008)	Water temperature: USGS site 14186200 (U.S. Geological Survey, 2026); Green Peter Lake elevation: USGS site 14186100 (U.S. Geological Survey, 2026)	-
2016	Observed, model of observed conditions	2008 BiOp operation (National Marine Fisheries Service, 2008)	Water temperature: USGS site 14186200 (U.S. Geological Survey, 2026); Green Peter Lake elevation: USGS site 14186100 (U.S. Geological Survey, 2026); floating thermistor profiles in Green Peter Lake: USACE DataQuery 2.0 (U.S. Army Corps of Engineers, 2026); Middle Santiam River inflow: USGS site 14185800 (U.S. Geological Survey, 2026)	Fully calibrated CE-QUAL-W2 model (Stratton Garvin et al., 2023a, 2023b)
2023	Observed, model of observed conditions	Deep drawdown	Water temperature: USGS site 14186200 (U.S. Geological Survey, 2026); Green Peter Lake elevation: USGS site 14186100 (U.S. Geological Survey, 2026); floating thermistor profiles in Green Peter Lake: USACE DataQuery 2.0 (U.S. Army Corps of Engineers, 2026); Middle Santiam River inflow: USGS site 14185800 (U.S. Geological Survey, 2026)	2023 adjusted model (Bartelt et al., 2024)

2024	Observed	Deep drawdown	Water temperature: USGS site 14186200 (U.S. Geological Survey, 2026); Green Peter Lake elevation: USGS site 14186100 (U.S. Geological Survey, 2026)	-
2025	Observed	Deep drawdown	Water temperature: USGS site 14186200 (U.S. Geological Survey, 2026); Green Peter Lake elevation: USGS site 14186100 (U.S. Geological Survey, 2026); fixed elevation thermistor data in Green Peter Lake (N. Buccola, USACE, unpublished data, 2026)*	-
Hypothetical drawdown scenario	Modeled	Deep drawdown, NOV15: earliest drawdown date	-	2023 adjusted model (Bartelt et al., 2024) Model inputs blend of spring 2024, 2023 data
Hypothetical drawdown scenario	Modeled	Deep drawdown, DEC01: delayed and accelerated drawdown	-	2023 adjusted model (Bartelt et al., 2024) Model inputs were a blend of spring 2024, 2023 data
Hypothetical drawdown scenario	Modeled	Deep drawdown, DEC15: latest drawdown date	-	2023 adjusted model (Bartelt et al., 2024) Model inputs were a blend of spring 2024 and 2023 data

*Data are available upon request by contacting U.S. Army Corps of Engineers at DLL-CENWP-Media-Desk@usace.army.mil.

Hydroclimatic conditions

Unregulated streamflow and water temperature data for Quartzville Creek immediately upstream of Green Peter Lake (USGS site 14185900; U.S. Geological Survey, 2026; Figure 1), one of the primary inflow

sources, provide an indication of hydroclimatic context for interpreting reservoir conditions and release temperatures across the study years (Figure 2). The years 2011, 2015, and 2016 were selected to represent pre-drawdown conditions during a cool and wet, hot and dry, and warm and normal year, respectively (refer to Stratton Garvin and Rounds [2022] for additional explanation about year types). Using Quartzville Creek streamflow and water temperature data as a proxy for hydroclimatic conditions, the three drawdown years (2023, 2024, 2025) appear to be relatively average and similar to 2016, with 2025 appearing warmer and drier than average and 2023 having a period of above-average precipitation and below-average temperatures in early spring (Figure 2).

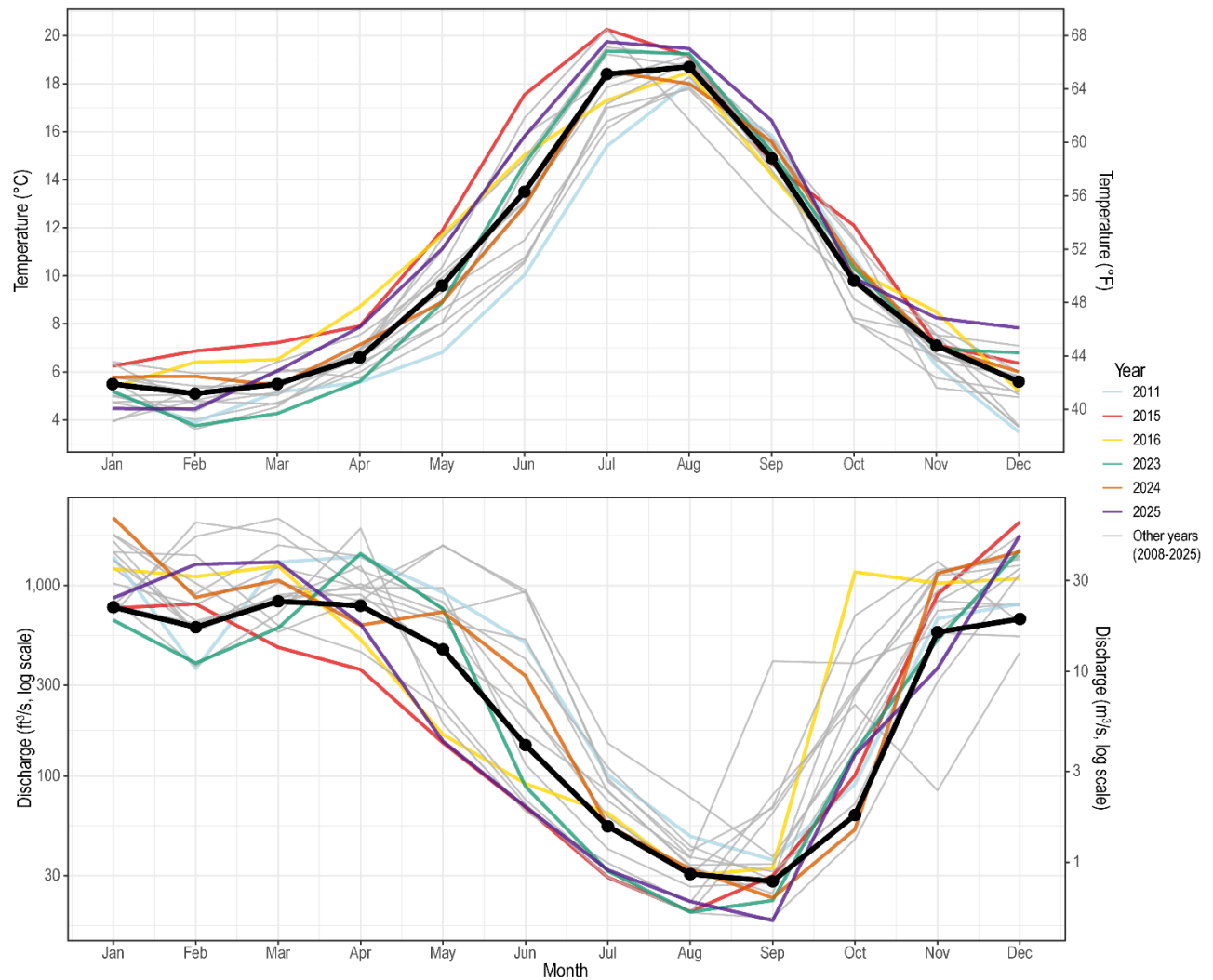


Figure 2 Mean monthly temperature (top) and discharge (bottom) at Quartzville Creek (USGS site 14185900; U.S. Geological Survey, 2026), a tributary that flows into Green Peter Lake. The black line represents the median for all years for 2008–2025. Colored lines represent the monthly mean temperature for years referenced in this study, with other years for 2008–2025 shown in light grey. The years 2011, 2015, and 2016 were cool and wet, hot and dry, and warm and normal years, respectively (Stratton Garvin and Rounds, 2022).

CE-QUAL-W2 Modeling

This study used CE-QUAL-W2 version 4.2 (USGS edition 7), a two-dimensional hydrodynamic model that simulates reservoir water levels, flows, and temperatures, to simulate the conditions in Green Peter and Foster Lakes (Wells, 2019; Stratton Garvin et al., 2023a). CE-QUAL-W2 has been extensively applied to water temperature modeling of rivers and lakes in the Willamette River Basin and hundreds of other waterbodies worldwide (Wells, 2026).

The Green Peter and Foster Lakes model was originally developed by WEST Consultants, Inc. (2005), updated by USGS in 2013 (Buccola et al., 2013) and 2021 (Sullivan and Rounds, 2021) and subsequently refined and calibrated for calendar years 2011, 2015, and 2016 (Stratton Garvin et al., 2023a, 2023b). These calibrated models provide the foundation for the modeling scenarios evaluated in this study.

The fully calibrated 2016 model was used to supplement measured data from 2016 to better understand the reservoir processes driving observed release temperatures (refer to Stratton Garvin et al. [2023a] for documentation of model inputs, calibration, and model fit). However, the model was calibrated for the years 2011, 2015, and 2016 under conditions that did not include a deep drawdown. When applied to 2023, which included a deep drawdown and the use of dam outlets not previously implemented, the model did not adequately capture the thermal structure in Green Peter Lake or the timing of increased release temperatures from Green Peter Dam. Adjustments to input parameters were therefore made to improve the 2023 model fit. Refer to S2 Appendix and Bartelt et al. (2024) for a description of the model adjustments and model fit. The adjusted model was used to simulate observed conditions during 2023 and for the three drawdown-timing scenarios.

Drawdown timing model scenarios

Three deep drawdown scenarios were modeled with the same hydroclimatic inputs but different timings for the reservoir drawdown to isolate the effects of those different drawdown timings on release temperatures, particularly during the autumn spawning period. Data sources and model input datasets are documented in Bartelt et al. (2024) and Stratton Garvin et al. (2023a, 2023b). Streamflow, temperature, and meteorological inputs for the model used 2024 data from January 1 through April 2 and 2023 data for the remainder of the calendar year, because the modeling was conducted in spring of 2024 to predict potential thermal conditions during the 2024 deep drawdown.

In the first scenario (NOV15), the water level in Green Peter Lake was drawn down to an elevation of 237.7 m (780 ft) NGVD29 (9.1 m above the RO outlet elevation) by November 15. In the second scenario

(DEC01), the deep drawdown was delayed, with the drawdown rate accelerated to reach an elevation of 237.7 m NGVD29 by December 1. In the third scenario (DEC15), the deep drawdown was further delayed to reach an elevation of 237.7 m NGVD29 by December 15.

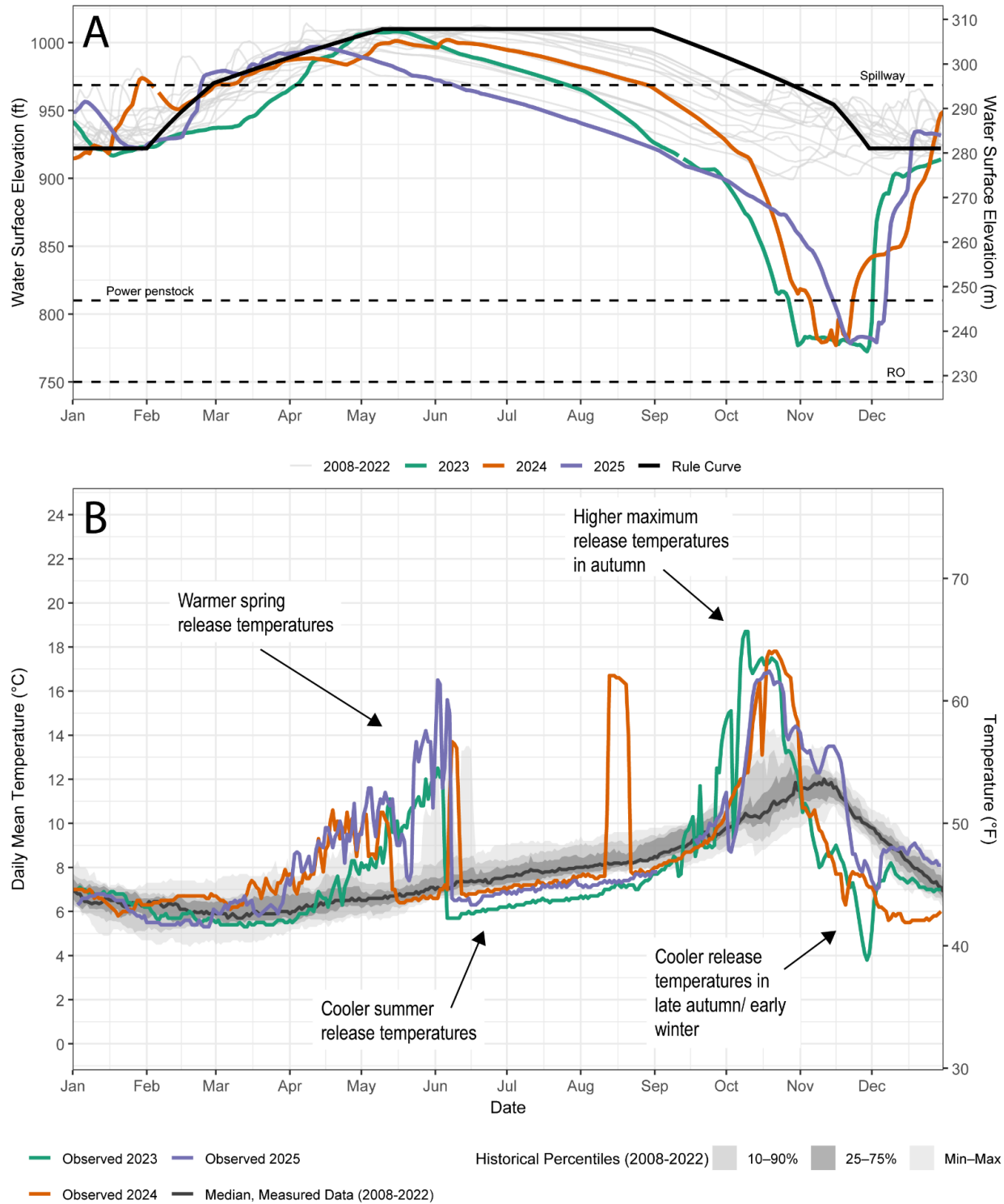
Results and discussion

Observed seasonal release temperature responses to deep drawdown operations

Deep drawdowns at Green Peter Dam during 2023–2025 produced distinct changes in the timing and magnitude of release temperatures relative to pre-drawdown operations, reflecting the close coupling between reservoir thermal conditions and the sequence of outlets used during each operational period. To facilitate downstream passage of juvenile salmon, Green Peter Lake was drawn down to approximately 236.2 m (minimum water surface elevation reached was 235.3 m, 236.8 m, and 237.1 m, for 2023, 2024, and 2025 respectively), which is 44.8 m lower than the established minimum conservation pool of 281 m. Relative to the historical operations driven by the 2008 Biological Opinion (BiOp: National Marine Fisheries Service, 2008), release temperatures during 2023-2025 were warmer in late spring and early

255 summer, cooler during summer, reached higher maximum values in autumn, and declined more rapidly in
256 late autumn and early winter (Figure 3).

257



258

259 *Figure 3. A) Time series of water surface elevation (NGVD29) of Green Peter Lake for 2023, 2024, and 2025 (USGS site*
 260 *14186100; U.S. Geological Survey, 2026). The black line shows the rule curve for Green Peter Lake (USACE DataQuery 2.0;*
 261 *U.S. Army Corps of Engineers, 2026). B) Time series of temperature released from Green Peter Dam for 2023, 2024, and 2025*
 262 *(USGS site 14186200; U.S. Geological Survey, 2026). Grey bands show the historical temperature range for 2008–2022 (pre*
 263 *drawdown; USGS site 14186200; U.S. Geological Survey, 2026).*

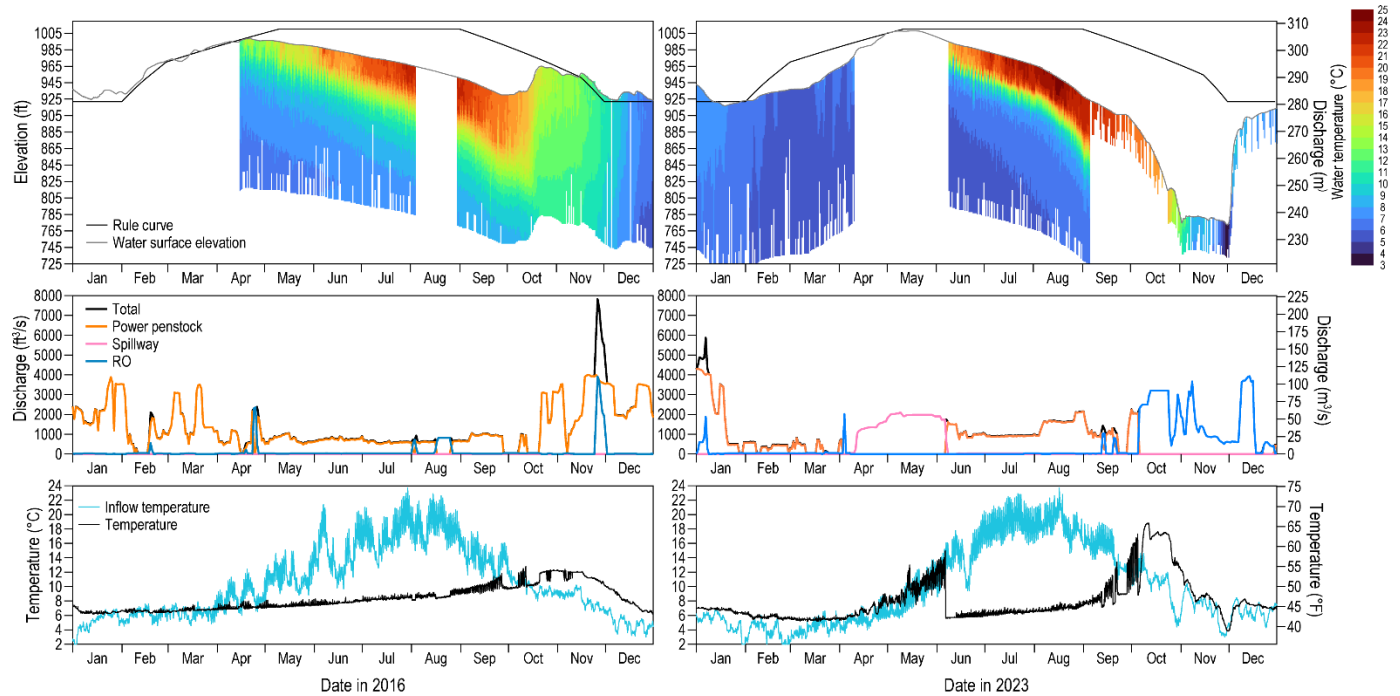
Mean monthly release temperatures differed between pre-drawdown and drawdown years from April through December (Table 2). The most pronounced difference occurred in October, when mean monthly temperatures during drawdown years (14.0–15.7 °C) substantially exceeded those from pre-drawdown years (9.4–12.8 °C). The maximum daily mean water temperature during drawdown years (18.7 °C, 17.8 °C, and 16.9 °C for 2023, 2024, and 2025, respectively) occurred approximately 1-3 weeks earlier than in pre-drawdown years and exceeded the upper bounds of the pre-drawdown historical record (Table 2, Figure 3).

Table 2. Summary of observed water temperatures immediately downstream of Green Peter Dam at USGS site 14186200 (U.S. Geological Survey, 2026), indicating release temperatures from the dam. The table includes monthly mean water temperature, maximum daily mean temperature, and date of maximum daily mean temperature for three pre-drawdown years (2011, 2015, 2016), which represent cool and wet, hot and dry, and warm but average wetness hydroclimatic years, respectively (Stratton Garvin and Rounds, 2022), and the three drawdown years (2023, 2024, 2025) at Green Peter Dam. Cell shading represents a blue-white-red color gradient scaled to the range of monthly mean water temperature values across all years shown, with blue indicating lower values, white indicating the median value, and red indicating higher values.

	Monthly mean water temperature(°C)										Maximum daily mean water temperature (°C)	Date of maximum daily mean water temperature (°C)
Operation	Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Pre-drawdown	2011	6.0	6.5	7.1	7.6	7.9	8.2	9.4	10.8	8.9	12.3	11/15/2011
	2015	7.7	8.1	8.7	9.1	9.2	10.0	12.8	11.1	8.6	14.3	10/28/2015
	2016	7.1	7.4	7.8	8.3	8.7	10.0	11.0	11.5	7.9	12.2	10/28/2016
Drawdown	2023	6.6	9.7	7.1	6.4	7.0	9.1	15.7	8.2	7.2	18.7	10/10/2023
	2024	8.7	7.8	7.8	7.3	10.3	8.8	14.7	8.6	5.9	17.8	10/19/2024
	2025	8.8	10.9	8.6	7.1	7.4	9.4	14.0	11.7	8.4	16.9	10/20/2025

To illustrate the reservoir conditions and physical processes underlying these differences, conditions during 2016 and 2023 are compared as representative pre-drawdown and drawdown years, respectively, in Figures 4 and 5. Where possible, interpretation relies primarily on measured data (Figure 4), but is

282 supplemented by model results for periods when gaps exist in the measured reservoir temperature profiles
 283 (Figure 5).



284
 285 *Figure 4. Time series of measured temperature, water surface elevation, and outflow discharge for 2016 (left) and 2023 (right)*
 286 *for Green Peter Lake. The top plot shows water surface elevations (NGVD29; USGS site 14186100, U.S. Geological Survey,*
 287 *2026) and vertical profiles of reservoir water temperature over time (refer to SI Appendix for thermistor sensor spacing; USACE*
 288 *DataQuery 2.0, U.S. Army Corps of Engineers, 2026). Temperature measurements were interpolated to 1-ft vertical increments,*
 289 *and the lower boundary of each colormap represents the elevation of the lowest measured data point for that date. Areas that are*
 290 *white represent periods where temperature profile data were not available. The middle plot shows outflow discharge over time*
 291 *(USACE DataQuery 2.0, U.S. Army Corps of Engineers, 2026). The bottom plot shows the release temperatures from Green Peter*
 292 *Dam (USGS site 14186200; U.S. Geological Survey, 2026), with inflow temperatures from the Middle Santiam River in blue*
 293 *(USGS site 14185800; U.S. Geological Survey, 2026).*

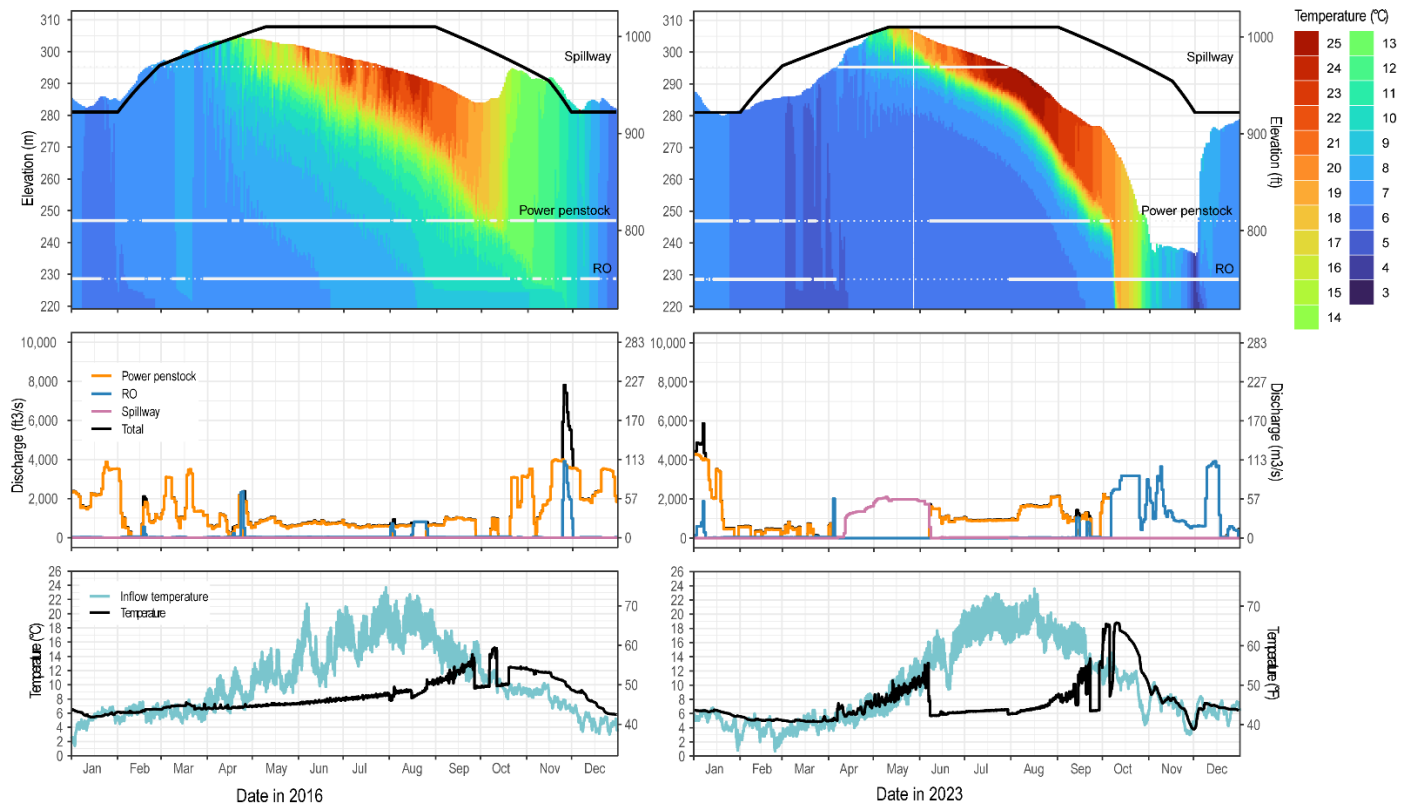


Figure 5. Time series of modeled temperature, water surface elevation, and discharge for modeled results for 2016 (left; Stratton Garvin et al., 2023a, 2023b) and 2023 (right; Bartelt et al., 2024) for Green Peter Lake. The top plot shows water surface elevations (NGVD29) and vertical profiles of reservoir water temperature over time. White horizontal lines indicate the elevation of each dam outlet and when any given outlet was in use. The middle plot shows outflow discharge over time. The bottom plot shows the release temperatures from Green Peter Dam, with inflow temperatures from the Middle Santiam River in blue.

Physical processes driving seasonal release temperature patterns

Warmer late spring and early summer release temperatures

Green Peter Lake was isothermal in January in both 2016 and 2023, with stratification developing in spring (approximately April-May) as heat began to accumulate in the epilimnion (Figures 4 and 5). Under pre-drawdown operations in 2016, outflow was routed almost exclusively through the power penstock throughout the year, releasing cool hypolimnetic water through spring and into summer (Figures 4 and 5). During the 2023 drawdown, the spillway was used from early April through early June (Figures 4 and 5). Because the water surface was near the spillway crest elevation during that period, warmer water was released through the spillway as the epilimnion was warming, resulting in release temperatures substantially higher than those characteristic of pre-drawdown operations for the same period (Figure 3B).

Release temperatures through the spillway increased with the warming epilimnion through early June when spillway use was discontinued (Figures 4 and 5).

In Green Peter Lake and as is typical in most reservoirs, the thermocline tends to deepen and thereby causes the epilimnion to thicken throughout the summer as heat accumulates in the epilimnion (Figures 4 and 5). At the same time, dam operations cause water surface elevations to slowly decrease during the typically dry summers of western Oregon because outflows often are larger than inflows to the reservoir. The export of epilimnetic heat through the spillway in spring has implications for subsequent thermal conditions later in the season. CE-QUAL-W2 model results (Figure 5) suggest that the export of epilimnetic heat via the spillway in 2023 helped maintain a thinner and cooler epilimnion and a shallower thermocline relative to 2016. The degree to which the reservoir fills during spring determines whether and to what extent the spillway can be used for this purpose, because the water surface elevation must be above the spillway crest elevation (295.3 m; Figure 1B) to retain use of the spillway. In dry years when the reservoir does not fill completely, opportunities for exporting epilimnetic heat through the spillway may be limited.

Cooler summer release temperatures

A sharp decrease in release temperature from approximately 15 to 6 °C occurred in 2023 in early June (Figures 3-5) when outlet use changed primarily from the spillway to the power penstock and releases transitioned from epilimnetic to hypolimnetic water (Figures 4 and 5). While summer release temperatures from Green Peter Dam are generally cool and much cooler than inflow temperatures under both operational regimes (Figure 5), a pattern typical of hypolimnetic-releasing dams, observed release temperatures for early June through August during the drawdown years were colder than the pre-drawdown historical ranges (Figure 3). For 2023 specifically, hydroclimatic conditions are likely a primary driver of cooler release temperatures because of cool inflows to the reservoir in spring as well as slow development and warming of the epilimnion (Figure 5). Dam operations likely contributed to the relatively lower summer release temperatures in 2023 and other drawdown years because use of the

spillway (rather than the power penstock) from early April through early June exported near-surface water instead of hypolimnetic water, thus preserving the cooler hypolimnetic volume that otherwise would be progressively released (and somewhat diminished) through the power penstock during this period under pre-drawdown operations (Figures 4 and 5).

Warmer maximum autumn release temperatures

The most notable difference between pre-drawdown and drawdown release temperatures occurred in autumn, when maximum daily values during 2023-2025 (16.9-18.7 °C) substantially exceeded those from pre-drawdown operations that typically ranged from about 12 to 14 °C (Figure 3, Table 2). In 2016 and 2023 the thermocline deepened throughout the summer as a result of two compounding processes. The epilimnion warmed and thickened naturally, while declining water surface elevations simultaneously brought the thermocline progressively deeper and closer to the lower outlets. Hypolimnetic water was exported continuously through the power penstock throughout this period (Figure 5). Under pre-drawdown operations in 2016, this process continued gradually through late summer and early autumn (Figures 4 and 5). Release temperatures in 2016 increased in September and October as the vertical withdrawal zone from power penstock releases began to intersect the base of the thermocline, but the descent of the thermocline was gradual. Some stratification and sufficient hypolimnetic water remained below the outlet to moderate the rising release temperatures (Figures 4 and 5). By mid-September, substantial natural cooling from the surface of the reservoir was occurring, which caused the release temperatures to gradually decrease in November and into December (Figures 4 and 5).

In 2023, releases through the power penstock increased in August, which accelerated the lowering of the water surface (Figures 4 and 5). By September, the elevation of the thermocline was low enough that the vertical withdrawal zone included progressively warmer water from the base of the thermocline, driving an increase in release temperatures (Figure 5). By early October, the thermocline had been pulled down to the power penstock elevation and release temperatures were within 2-3 °C of surface water temperatures (Figures 4 and 5). In early October, the primary outlet was changed to the RO (Figure 4). Initially, cooler

hypolimnetic water was released from the RO, but the cooler releases persisted only two to three days before the thermocline was pulled down to the elevation of the RO, the reservoir destratified, and the remaining heat from the epilimnion mixed throughout the water column (Figure 5). Release temperatures reached a maximum instantaneous value of 18.8 °C on October 10 (Figure 4).

Several factors influence the magnitude of maximum release temperatures in autumn, including how much heat remains in the epilimnion when the drawdown is initiated, the distance between the water surface and the thermocline to the active outlet elevation, the temperature difference between the epilimnion and hypolimnion, and the release rate through each outlet. These factors directly dictate the rate of descent of the water surface and thermocline and also the extent of the vertical withdrawal zone.

Cooler late autumn and early winter release temperatures

By mid-September, the epilimnion typically is cooling rapidly, which decreases the vertical density gradient (temperature difference) across the thermocline. A weaker density gradient is more easily overcome by a large discharge that creates a correspondingly large vertical withdrawal zone, which in turn can trigger an early turnover event that mixes water vertically and may eliminate any remaining options for releasing cooler water from deeper in the reservoir. In 2023, temperatures decreased rapidly after the thermocline was pulled down to the RO, the reservoir completed its turnover, and all remaining heat from the epilimnion was mixed vertically and released through the RO. At this point, reservoir inflows were seasonally cooler, and meteorological conditions caused further cooling within a smaller reservoir volume compared to pre-drawdown operations. The larger lake volume under pre-drawdown conditions at this time of year would have contained more heat and the larger volume would have slowed the natural cooling process. The cooling of a smaller reservoir volume in 2023 likely contributed to cooler late autumn and early winter release temperatures relative to pre-drawdown conditions (Figure 3). This late autumn temperature decrease was relatively rapid compared to the more gradual seasonal cooling observed in pre-drawdown years (Figures 4 and 5).

Potential thermal implications for spring Chinook salmon and egg incubation

Spring Chinook salmon spawn in high densities in the South Santiam River downstream of Foster Dam (National Marine Fisheries Service, 2008; Oregon Department of Fish & Wildlife and U.S. Army Corps of Engineers [USACE], 2019), and the substantially warmer autumn release temperatures associated with deep drawdown operations raise the question of whether conditions approach or exceed thermal thresholds for harm to salmonid egg incubation. Observed daily mean release temperatures from Green Peter and Foster Dams for 2008-2025 were compared with temperature thresholds established by Martin et al. (2017): T_{crit} or the temperature below which no mortality due to temperature occurs during egg incubation. Martin et al. (2017) identified a T_{crit} value of 15.4 °C in a laboratory setting and a more conservative value of 12.0 °C in a field setting. The discrepancy between these estimates arises primarily because oxygen supply to developing embryos is strongly dependent on overlying water velocity, and eggs incubating in natural gravel redds are subject to lower velocities and receive lower oxygen fluxes than those in laboratory settings, making them more vulnerable to warm temperatures (Martin et al., 2017). In the Willamette River Basin, the timing for spawning and egg incubation generally extends from about September 1st through about March, but for the purpose of this study we evaluated the T_{crit} metric for the period of September 1st through December 31st, because this covers the main timeframe affected by drawdown operations.

Daily mean release temperatures from both dams frequently exceeded the field T_{crit} (12 °C) during September-December, indicating the generally warm autumn release temperatures characteristic of both operational regimes (Figure 6). Exceedance of the laboratory T_{crit} of 15.4 °C, however, occurred exclusively during the three drawdown years. Green Peter Dam release temperatures exceeded this threshold for approximately 18, 13, and 14 days during the September 1st through December 31st period in 2023, 2024, and 2025, respectively. No such exceedances occurred under 2008 BiOp driven pre-

drawdown operations, indicating that warmer autumn releases from deep drawdown operations could represent a meaningful increase in the thermal stress to incubating eggs relative to historical conditions.

Several interpretive caveats apply to this threshold analysis. While Green Peter Dam release temperatures strongly influence release temperatures from Foster Dam, Foster Lake residence time and dam operations buffer the Green Peter Dam release temperatures, generally resulting in cooler maximum release temperatures in autumn downstream of Foster Dam relative to Green Peter Dam. For example, in 2025, Green Peter Dam release temperatures exceeded 15.4 °C for 14 days during the September through December period whereas no days exceeded 15.4 °C immediately downstream of Foster Dam (Figure 6). However, Foster Dam also buffers the unseasonably cool mid-summer release temperatures from Green Peter Dam, resulting in early autumn temperatures immediately downstream of Foster Dam that are warmer than those downstream of Green Peter Dam. Consequently, exceedance of the 12°C field T_{crit} threshold is generally more frequent immediately downstream of Foster Dam, particularly in September when temperatures downstream of Green Peter Dam rarely exceed 12 °C at that time of year (Figure 6). September exceedances of 12 °C downstream of Foster Dam should be interpreted cautiously, however, because a) September is early in the spawning and egg incubation period and eggs may not yet be present in redds, and b) South Santiam River inflow temperatures also regularly exceed 12 °C in September independent of dam operations (Figure 6). In addition, the intergravel water temperatures that redds are exposed to may be cooler than the mixed release temperatures due to hyporheic exchange and groundwater inputs (Malcolm et al., 2002; Poole and Berman, 2001). Critical threshold exceedance should not be interpreted as a direct prediction of egg mortality, but rather as a helpful metric for characterizing the frequency and duration of thermal conditions that are potentially stressful or harmful for incubating eggs in redds.

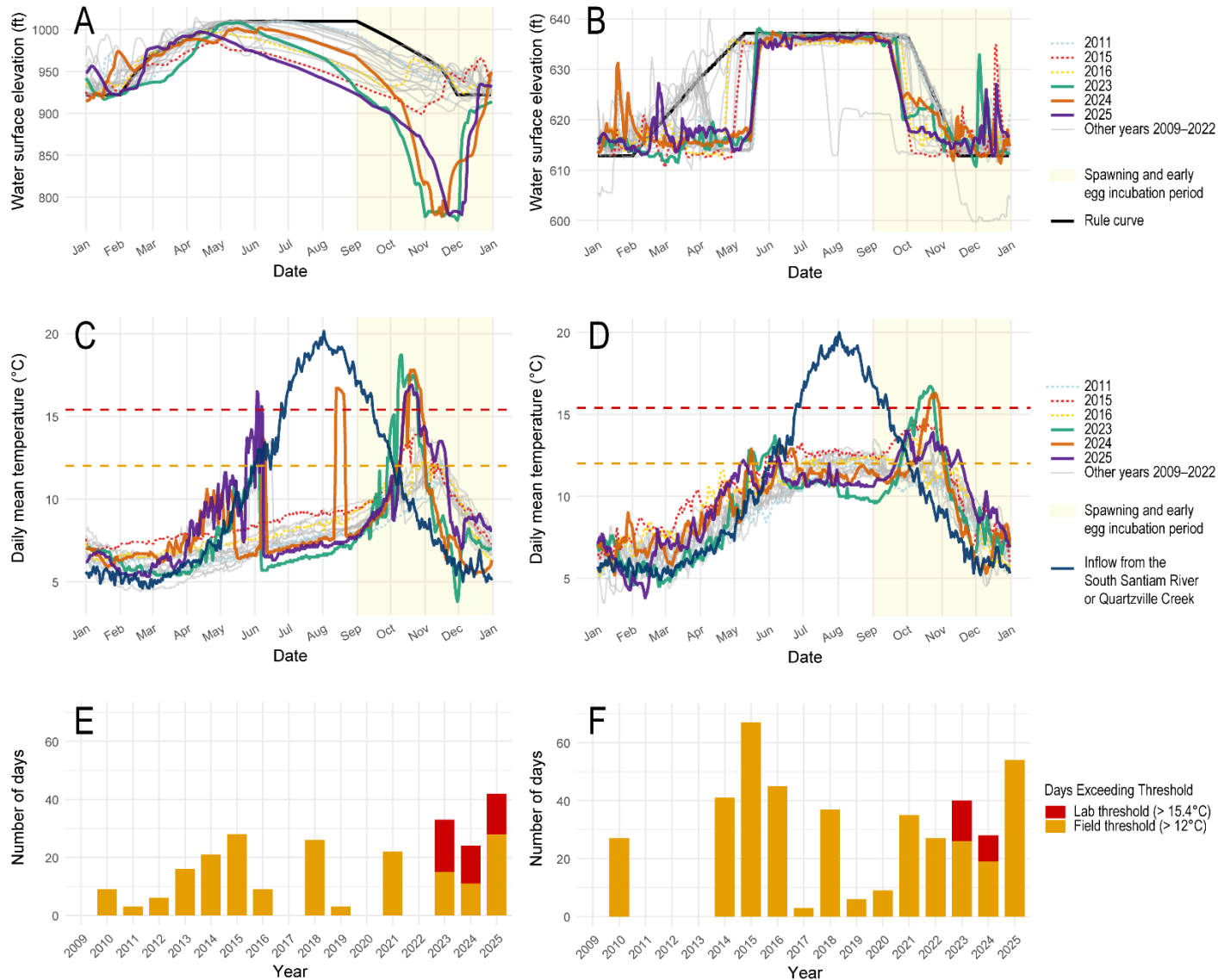
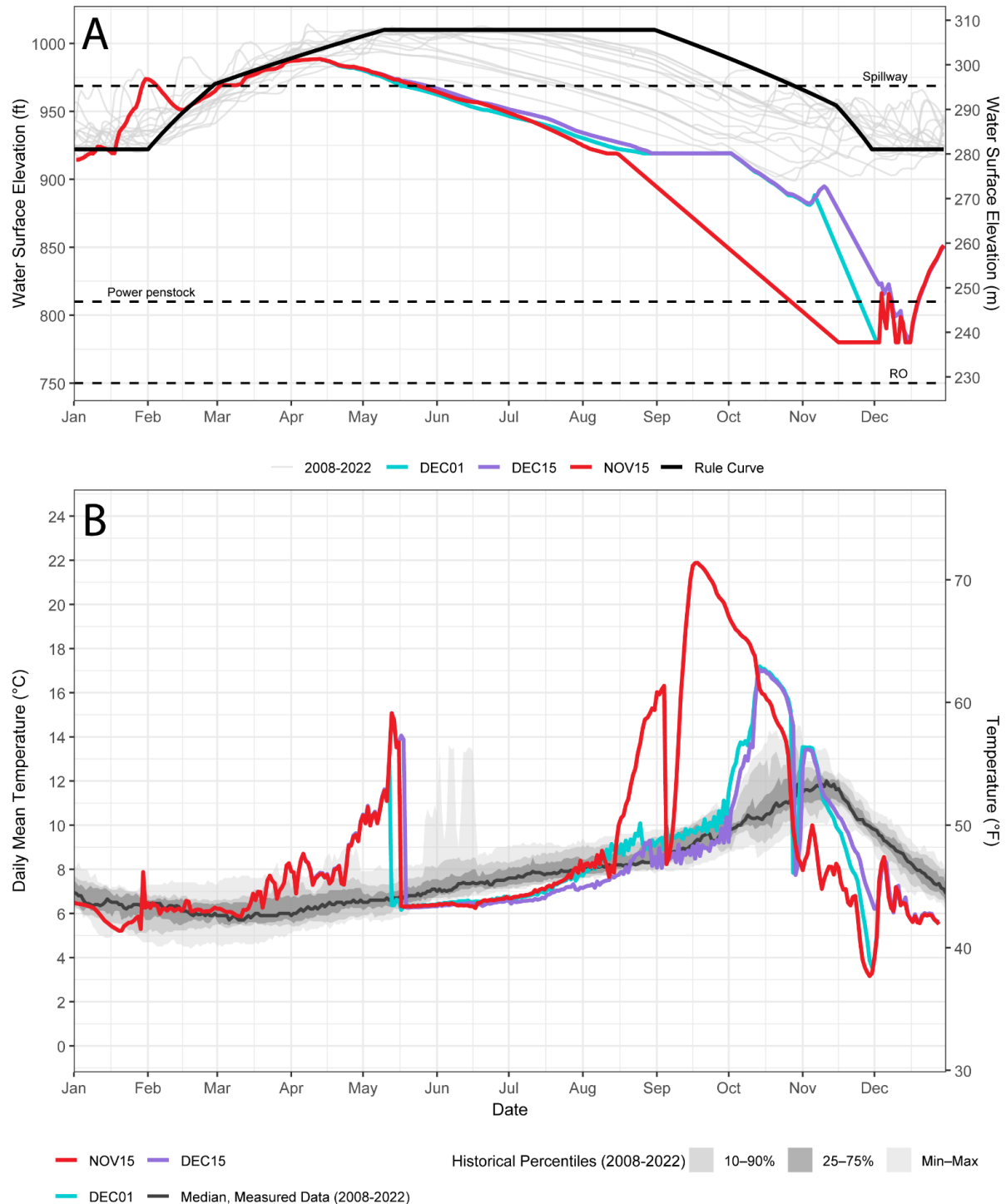


Figure 6. Graphs of water levels (NGVD29), temperatures, and critical egg-incubation thresholds for Green Peter Dam (A, C, E) and Foster Dam (B, D, F). The top row shows water surface elevation of Green Peter Lake (A; USACE DataQuery 2.0 prior to 2013, USGS site 14186100 from 2013 onward; U.S. Army Corps of Engineers, 2026; U.S. Geological Survey, 2026) and Foster Lake (B; USACE DataQuery 2.0 prior to 2013, USGS site 14186600 from 2013 onward; U.S. Army Corps of Engineers, 2026; U.S. Geological Survey, 2026). The black line shows the rule curve elevation (USACE DataQuery 2.0; U.S. Army Corps of Engineers, 2026). The middle row shows daily mean temperature below Green Peter Dam (C; USGS site 14186200; U.S. Geological Survey, 2026) and Foster Dam (D; USGS site 14187200; U.S. Geological Survey, 2026). The dark blue line shows inflow temperature to Green Peter Lake from Quartzville Creek (C; USGS site 14185900; U.S. Geological Survey, 2026) and to Foster Lake from the South Santiam River (D; USGS site 14185000; U.S. Geological Survey, 2026). Light yellow shading represents the spawning and egg incubation period. Dashed orange and red lines represent the laboratory (15.4 °C) and field (12 °C) T_{crit} threshold values from Martin et al., (2017). The bottom row shows the number of days that release temperatures from Green Peter Dam (E) and Foster Dam (F) were above T_{crit} values during the 121-day spawning and early egg incubation period evaluated in this study of September 1st through December 31st for 2009 - 2025.

Sensitivity of peak autumn release temperature to drawdown timing

To better understand the effects of drawdown timing on warm autumn release temperatures, we used three CE-QUAL-W2 model scenarios with identical hydroclimatic inputs but varied drawdown timing to isolate and quantify the effect of drawdown timing on peak autumn release temperatures. In all three scenarios, the spillway was used from March through mid-May, which allowed the release of warming epilimnetic water as spring progressed (Figures 7 and 8). Release temperatures dropped sharply when the water surface decreased below the spillway elevation and releases were switched to the power penstock, thus releasing cool, hypolimnetic water (Figures 7 and 8). The power penstock was the only outlet used in each scenario for June, July and early August. During this period, the water level in the reservoir gradually declined and the thermocline was progressively lowered but remained above the power penstock elevation (Figure 8).

While the power penstock was releasing cool hypolimnetic water, surface water temperatures in the epilimnion increased throughout the summer, reaching a maximum of over 26 °C in mid-August (Figure 8). Up until this point in mid-August, the three drawdown timing scenarios were relatively similar (Figure 8). After mid-August, however, the scenarios varied more significantly.



460

461 *Figure 7. A) Time series of target water surface elevations (NGVD29) in Green Peter Lake for the three drawdown timing*
 462 *scenarios that use the 2023 adjusted model (Bartelt et al., 2024). The black line shows the rule curve for Green Peter Lake*
 463 *(USACE DataQuery 2.0; U.S. Army Corps of Engineers, 2026), and grey lines show water surface elevations for 2008 – 2022*
 464 *(USACE DataQuery 2.0 prior to 2013, USGS site 14186100 from 2013 onward; U.S. Army Corps of Engineers, 2026; U.S.*
 465 *Geological Survey, 2026). B) Time series of modeled Green Peter Dam release temperatures for the three drawdown timing*
 466 *scenarios (Bartelt et al., 2024). Grey bands represent pre-drawdown observed release temperature ranges for 2008-2022 (USGS*
 467 *site 14186200; U.S. Geological Survey, 2026).*

In the NOV15 scenario, drawdown began in mid-August when surface temperatures were at their highest. An increased discharge through the power penstock of about 53.8 m³/s (1900 ft³/s) quickly pulled the thermocline down to a point near the outlet elevation, causing release temperatures to rise rapidly as warmer water from the epilimnion was mixed into the release (Figure 8). When the RO began to be used in the NOV15 scenario in early September, a brief period of cold-water release occurred before the thermocline descended to the RO elevation, inducing reservoir turnover and rapidly increasing release temperatures that reached a maximum daily mean temperature of 21.9 °C on September 18 (Table 3). Following turnover, the reservoir subsequently released warm water through the RO until the lake finally lost enough heat to its surrounding environment and a more natural seasonal temperature release was achieved in late October and November.

Table 3. Modeled monthly mean temperature, maximum daily mean temperature, and date of maximum daily mean temperature for the three Green Peter Lake drawdown timing scenarios that use the 2023 adjusted model (Bartelt et al., 2024). Cell shading represents a blue-white-red color gradient scaled to the range of monthly mean water temperature values across all scenarios shown, with blue indicating lower values, white indicating the median value, and red indicating higher values.

	Monthly mean water temperature (°C)										Maximum daily mean water temperature (°C)	Date of maximum daily mean water temperature (°C)
Scenario	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec			
NOV15	8.1	9.1	6.5	7.2	10.7	17.8	15.5	7.0	6.2	21.9	9/18	
DEC01	8.1	8.1	6.6	7.1	8.8	9.8	14.4	9.6	6.2	17.2	10/14	
DEC15	8.2	9.6	6.4	6.8	7.9	8.9	14.0	10.4	6.4	17.1	10/14	

The DEC01 and DEC15 scenarios imposed a more delayed drawdown of the lake and exhibited markedly different thermal responses. Like the NOV15 scenario, surface water temperatures in Green Peter Lake for these two scenarios were at their highest in mid-August. However, in contrast to the NOV15 scenario, the reservoir elevation was held higher through August and September while minimal flows were released from the reservoir. This allowed more heat to be naturally released from the surface of the lake to its surrounding environment as air temperatures and solar radiation fluxes declined seasonally.

In both the DEC01 and DEC15 scenarios, when the drawdown was initiated during October through increased releases of about 53.8 m³/s (1900 ft³/s) through the power penstock, the thermocline was drawn downward toward the outlet, causing release temperatures to quickly increase as warmer epilimnetic

water was entrained into the withdrawal. Maximum daily mean release temperatures occurred during this period and were 4.7 °C and 4.8 °C cooler than those from the NOV15 scenario for DEC01 and DEC15, respectively (Table 3), reflecting the effect of allowing the epilimnion to cool for an additional six weeks in late summer before initiating the drawdown (Figure 8). Subsequent RO operation followed a similar pattern to the NOV15 scenario, with a brief cold water release followed by further thermocline descent and lake turnover. Maximum release temperatures differed by only 0.1 °C between the DEC01 and DEC15 scenarios (Table 3) because they occurred when water was being released from the power penstock in October, before the RO was used and before the two scenarios diverged in the timing of the final drawdown. While not evaluated in the DEC01 and DEC15 scenarios, earlier use of the RO following drawdown initiation could have been timed to further reduce maximum release temperatures by releasing remaining hypolimnetic water before peak release temperatures occurred.

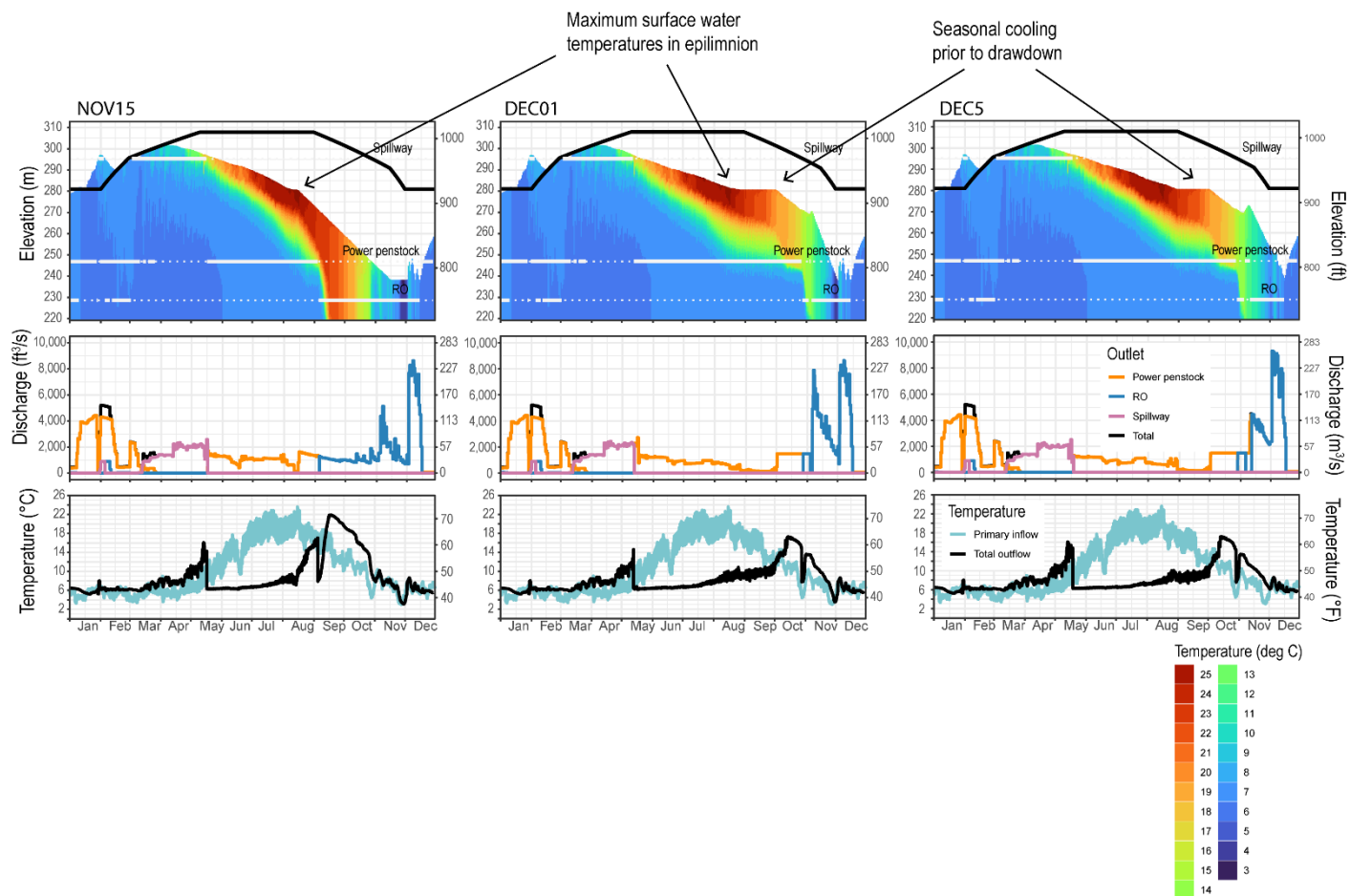


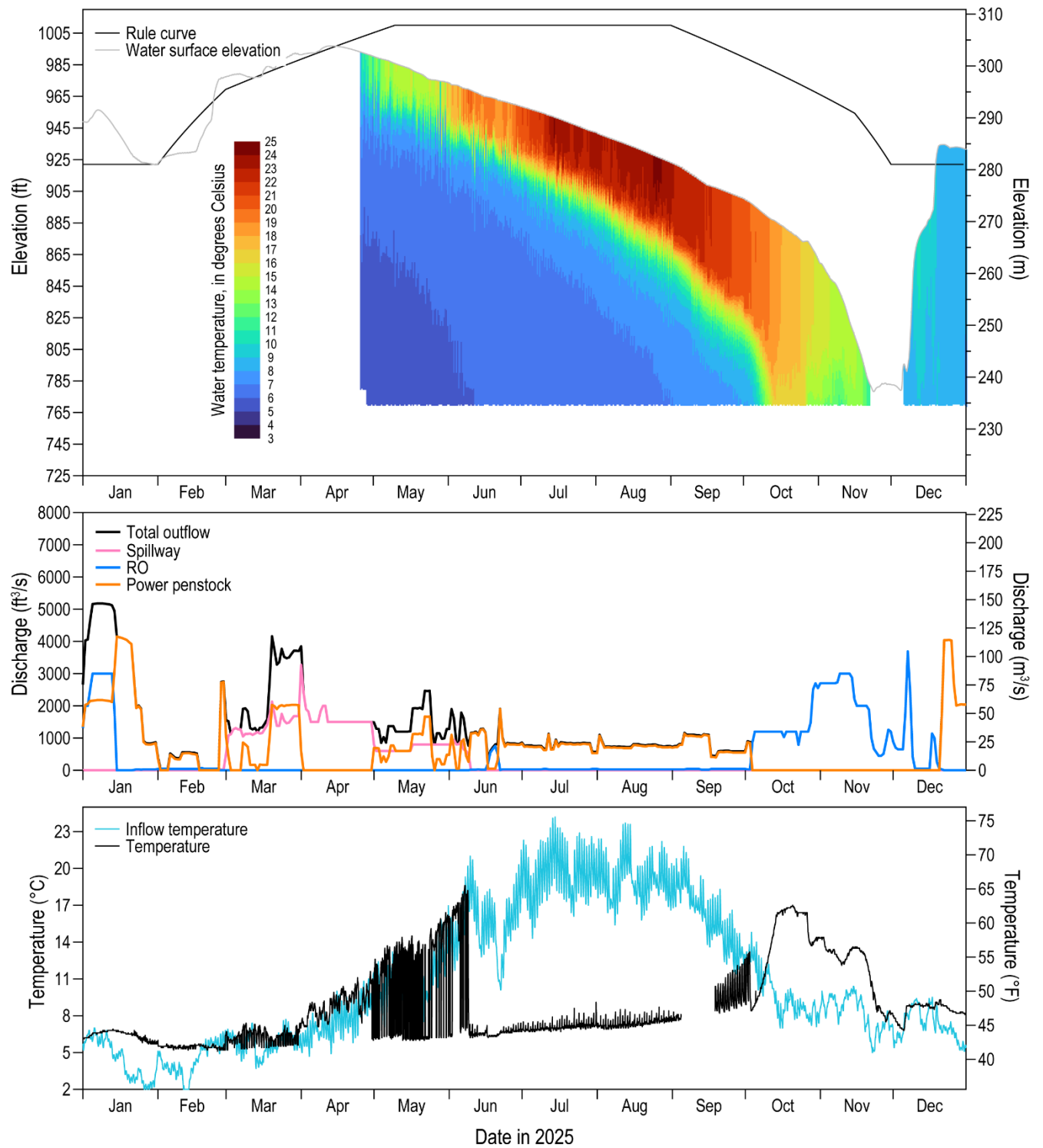
Figure 8. Time series of modeled temperature, elevation, and discharge for three drawdown scenarios (NOV15, DEC01, and DEC15) for Green Peter Lake that use the 2023 adjusted model (Bartelt et al., 2024). Each top plot shows water surface elevation (NGVD29) and reservoir water temperature profiles over time. White horizontal lines indicate the elevation of each dam outlet and when each outlet was in use. The middle row shows outflow discharge for the power penstock, spillway or RO, and total outflow. Each bottom plot shows the total release temperature in black, with inflow temperature from the Middle Santiam River in blue.

The hydroclimatic conditions used to drive these scenarios included inflows to fill the reservoir to rule curve in spring, the use of the spillway in March through mid-May, and meteorological conditions (cooler air temperatures, smaller short-wave solar insolation fluxes) in mid-August that caused the epilimnion to begin cooling naturally prior to drawdown initiation in the DEC01 and DEC15 scenarios. In drier or warmer years in which the reservoir does not sufficiently fill in the spring (for spillway usage) or in which the epilimnion does not cool substantially in late summer, the thermal benefits of delayed drawdown initiation would likely be more muted.

2025 observations in context of modeled drawdown timing scenarios

An evaluation of reservoir conditions and dam operations during the 2025 deep drawdown shows consistency with the drawdown timing model scenarios. Despite warmer and drier hydroclimatic conditions than in 2023 and 2024 (Figure 2), maximum autumn release temperatures in 2025 were lower than in either prior year (Figure 3B). In 2025, spillway use extended into June until the water surface elevation dropped below the spillway outlet, and spillway releases had mean daily temperatures that exceeded 16 °C (Figures 3B and 9), which likely helped delay and reduce the extent of subsequent warming in the epilimnion. Even though the reservoir elevation from late spring through summer was lower in 2025 than in 2023 and 2024 (Figure 3A), the final period of rapid drawdown to reach the target elevation of approximately 236.2 m by mid-November was approximately 2-4 weeks later compared with 2023-2024 (Figure 3A). Delaying the final drawdown meant keeping the water surface and thermocline higher and also keeping the vertical withdrawal zone smaller via reduced discharge relative to what is used during active drawdown. During the delay, the epilimnion was able to cool through September and part of October, and enough heat was released to the environment such that maximum release temperatures were lower than in 2023 and 2024 despite the warmer and drier hydroclimatic conditions

533 (Figure 2 and 9). Had the pool been held higher for a longer period to extend epilimnetic cooling,
534 maximum release temperatures might have been further reduced. The final drawdown in early October
535 was executed by routing all outflow through the RO. This rapidly lowered the water surface and
536 thermocline and released all remaining accessible cooler water from the hypolimnion. Blending releases
537 from the power penstock and RO, rather than a full, early transition to the RO, might have kept the
538 vertical withdrawal zone smaller and made more effective use of remaining hypolimnetic water to further
539 reduce peak release temperatures.



540

541 *Figure 9. Time series of measured temperatures, water surface elevations, and outflow discharges for Green Peter Lake in 2025.*
 542 *The top plot shows the water surface elevation (NGVD29; USGS site 14186100, U.S. Geological Survey, 2026) and vertical*
 543 *profiles of reservoir water temperature over time (refer to S1 Appendix for thermistor sensor spacing and data source).*
 544 *Temperature measurements were interpolated to 1-ft vertical increments, and the lower boundary of each colormap represents the*
 545 *elevation of the lowest measured data point for that date. Areas that are white represent periods where temperature profile data*

were not available. The middle plot shows outflow discharge over time (USACE DataQuery 2.0, U.S. Army Corps of Engineers, 2026). The bottom plot shows the release temperature from Green Peter Dam, with inflow temperature from the Middle Santiam in blue.

The 2025 thermal response is broadly consistent with the DEC01 and DEC15 model scenarios in which delayed drawdown following natural epilimnetic cooling produced meaningfully lower maximum autumn release temperatures. Together, the scenario modeling results and 2025 observations support the conclusion that delaying deep drawdown initiation until seasonal cooling of the epilimnion has occurred is an effective adaptive management strategy for reducing peak autumn release temperatures. Real-time monitoring of in-reservoir temperature profiles together with reservoir energy content calculations (discussed further below), could help to determine when sufficient epilimnetic cooling has occurred to initiate a deep drawdown while keeping release temperatures below a specified threshold.

Management implications

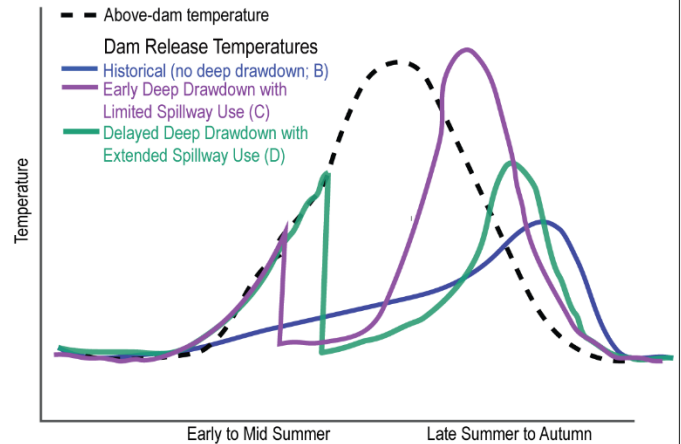
Results from the drawdown timing scenarios and measurements from 2025 point to a suite of inter-related reservoir conditions and operational factors that collectively determine release temperatures. This understanding could provide a basis for future management and monitoring activities at Green Peter Lake and inform reservoir management elsewhere. The magnitude of autumn release temperatures is essentially a function of (1) the amount of heat energy stored in the epilimnion at the time a deep drawdown is initiated, (2) the distances between the water surface and the thermocline and the active outlet, (3) the temperature difference between the epilimnion and hypolimnion, and (4) the release rate through each outlet. These factors dictate the rate of descent of the water surface elevation and the thermocline, as well as the likely extent of the vertical withdrawal zone. Some of the conditions that set the template for release temperatures are hydroclimatic conditions such as inflows and inflow temperatures, downstream use constraints such as minimum downstream flow requirements, and spring and summer dam operations. However, by the time autumn approaches and these conditions are established, release temperatures will be dictated by the factors listed above along with prevailing autumn meteorological conditions.

This study identifies two operational strategies to balance thermal tradeoffs associated with deep drawdowns. More specifically, these strategies may reduce peak autumn release temperatures associated with deep drawdown of a large reservoir, thereby providing potential to support downstream passage of juvenile Chinook salmon while reducing thermal harm to adult Chinook salmon and their redds in downstream reaches. First, releasing water from near-surface dam outlets starting in late spring and continuing as long as possible into summer reduces the accumulation of heat in the epilimnion. At Green Peter Lake, this entails utilizing the spillway in late spring and summer for as long as pool levels permit to export heat, minimizing epilimnion thickness and ultimately reducing autumn release temperatures. Effective use of this strategy also helps conserve hypolimnetic volume for later use. Second, delaying deep drawdown initiation as long as feasible to take advantage of seasonal cooling of the epilimnion allows more heat to be exported to the atmosphere rather than to downstream reaches. Together, these two distinct but complementary operational strategies could form the basis for adaptively managing reservoir thermal conditions and release temperatures to facilitate a deep reservoir drawdown, but would benefit from real-time understanding of reservoir thermal structure to determine the timing and release rates from various outlets. The contrasts among historical operations, an early deep drawdown, and a delayed deep drawdown, and their consequences for reservoir thermal structure and release temperatures are illustrated conceptually in Figure 10. For a practical example of what implementation of these strategies could look like at Green Peter Dam or other large stratified reservoirs with a spillway and multiple lower level outlets that require implementation of a deep reservoir drawdown refer to S4 Appendix.

Spring spill and delaying the deep drawdown complement a broader reservoir management approach in which operations are managed throughout the year with an explicit focus on retaining a cold-water pool and judiciously allocating cold water via hypolimnetic releases. Extending spring spill for as long as feasible conserves hypolimnetic volume and exports near-surface heat via the spillway. Delaying drawdown initiation for as long as feasible preserves access to that cold water for longer into late summer and autumn. This underlying principle of retaining and judiciously allocating a cold-water pool

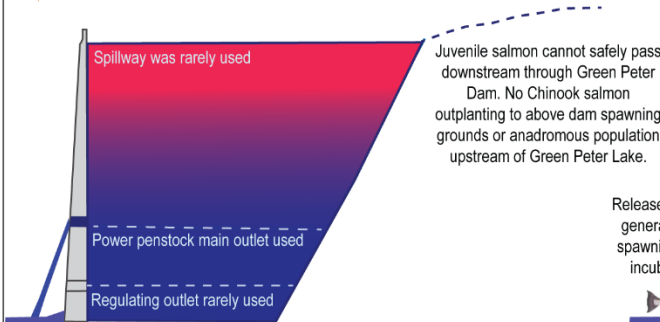
throughout the season is the same broader principle that underlies cold-water management at reservoirs such as Shasta Lake and Folsom Lake in California, where operators track and manage hypolimnetic volume throughout the season and blend releases across multiple outlet elevations using temperature control devices (TCDs) to stretch and utilize hypolimnetic releases through the period when it matters most for salmonids (National Marine Fisheries Service, 2024; U.S. Bureau of Reclamation, 2026). A comparable blending approach has been used at Detroit Lake, drawing on outlets at different elevations rather than a purpose-built TCD (Buccola et al., 2012). Dam operations are constrained by the specific infrastructure and considerations unique to each dam, so the feasibility of blending release temperatures across outlet elevations will vary. Nevertheless, year-round operational decisions could be guided by integrating distinct reservoir operations (such as deep drawdowns) within a broader reservoir management framework that is focused on preserving a cold-water pool.

A. Green Peter Dam and Generalized Water Temperature Conditions for Above Dam and Dam Releases under Different Operational Scenarios

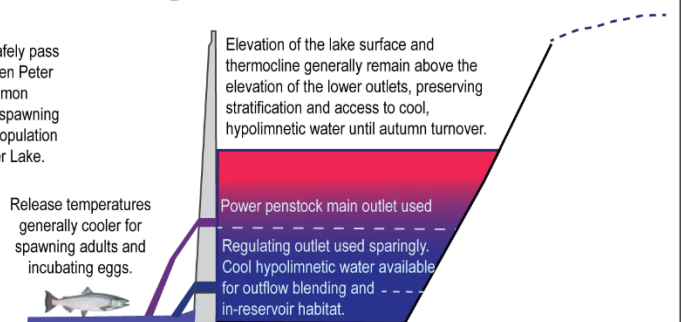


B. Historical dam operations according to rule curve with no deep drawdown

Early - Mid Summer

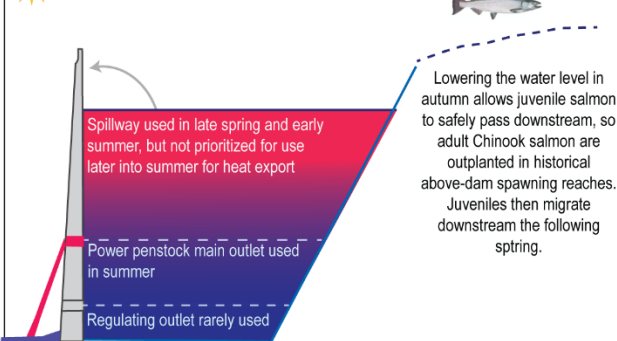


Late Summer to Autumn

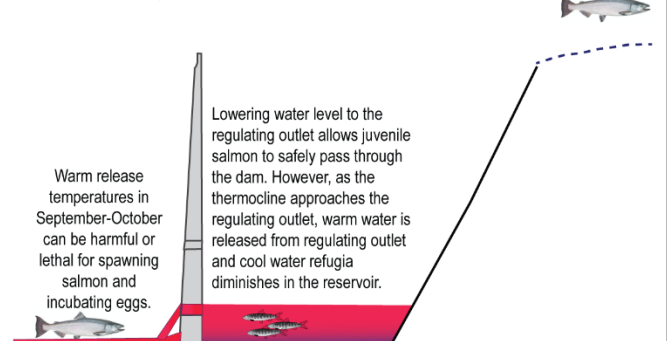


C. Early Deep Drawdown with Limited Spillway Use

Early - Mid Summer

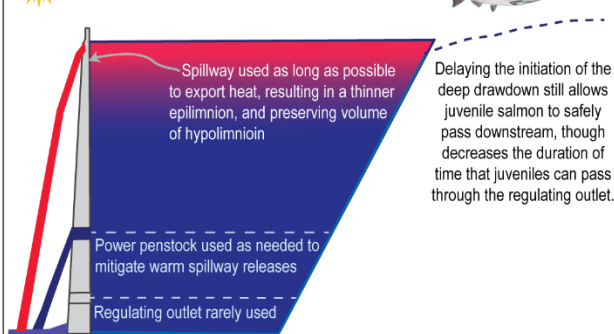


Late Summer to Autumn



D. Delayed Deep Drawdown with Extended Spillway Use

Early - Mid Summer



Late Summer to Autumn

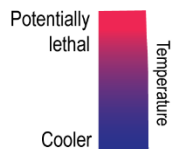
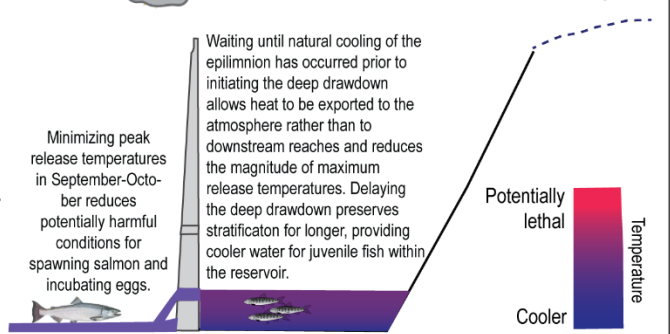


Figure 10. Conceptual diagram of reservoir thermal stratification and dam release temperatures under historical operations and deep drawdown scenarios at Green Peter Dam. (A) Aerial view of Green Peter Dam and Green Peter Lake, and generalized seasonal patterns of above-dam reservoir and below-dam release temperatures under historical, pre-drawdown operations, an early deep drawdown, and an idealized delayed deep drawdown. (B) Under historical operations without a deep drawdown, the lake surface and thermocline remain above the lower outlets through autumn, preserving stratification and maintaining safe release temperatures for spawning adults and incubating eggs, but juvenile salmon cannot pass downstream. (C) An early deep drawdown lowers the reservoir towards the regulating outlet in early-to-mid summer, allowing juvenile salmon to pass downstream, but as the thermocline approaches, the regulating outlet in late summer and autumn, warm water is released, and cool-water refugia within the reservoir diminish, producing release temperatures that can be harmful or lethal to spawning adults and incubating eggs. (D) A delayed deep drawdown combines two complementary strategies: using the spillway to export near-surface heat during early-to-mid summer, which thins the epilimnion and preserves hypolimnetic volume, and postponing the drawdown until natural cooling of the epilimnion has occurred. Together these minimize peak release temperatures in September–October while still facilitating downstream passage for juvenile Chinook salmon and provide cooler water for juvenile salmon remaining in the reservoir prior to downstream migration.

The extent to which these strategies can be implemented will depend on hydroclimatic conditions, infrastructure constraints on dam outlet usage (such as water level or head requirements to operate various outlets), downstream flow requirements, and other operational, regulatory, and institutional factors that may constrain or redirect dam operations. Successful implementation of these strategies would benefit from identifying an optimal range of surface cooling thresholds to minimize potentially harmful releases. Additionally, weighing the thermal benefits of delayed deep drawdowns for below-dam spawning salmon with any potential benefits of earlier deep drawdowns for juvenile salmon migrating downstream past Green Peter Dam would be useful to inform operations.

The deep drawdowns of Green Peter Lake from 2023-2025 represent a fundamental operational shift from prior decades, highlighting thermal consequences that cascade from the reservoir to downstream reaches during the window of Chinook salmon spawning and egg incubation. Because the competing objectives of providing downstream juvenile passage while protecting spawning adults and egg incubation are tightly linked through reservoir temperature dynamics, operational decisions made at any point in the season propagate forward in ways that are difficult to anticipate without a quantitative framework. A systems and life-cycle perspective that explicitly accounts for the close coupling among reservoir thermal conditions, dam operations, downstream release temperatures, and salmon life stages across the full annual cycle can be used to help navigate these tradeoffs. Process-based modeling combined with high-resolution in-reservoir and downstream temperature monitoring can be used to systematically quantify the potential effects of proposed dam operations and identify ways to minimize potentially harmful outcomes

while still achieving operational objectives. Process-based modeling can also be used to inform how to best implement a particular dam operation amid the many competing management constraints that are typical of large dams. For example, the competing constraints may include synchronizing dam operations with the life stages and thermal tolerances of salmon while fulfilling other authorized purposes of the dam and reservoir, accommodating engineering constraints on outlet usage and meeting downstream water user needs.

Major changes in dam operations such as deep drawdowns affect many aspects of the reservoir environment which must be evaluated both individually and holistically to develop balanced reservoir management strategies. Although this study focused on release temperatures and their implications for downstream Chinook salmon, the anomalously warm in-reservoir conditions during the 2023-2025 drawdowns (Figure 4) likely also negatively affected in-reservoir conditions for juvenile salmon prior to passage through the dam. A similar deep drawdown of Lookout Point Lake in 2023 destratified the reservoir and created uniformly warm, reservoir conditions, which adversely affected predation, survival and passage of juvenile Chinook salmon (Hance et al., 2024; Liss et al., 2020). Additionally, deep drawdowns at other Willamette River Basin reservoirs have driven major changes in reservoir sediment regimes, food webs and fish communities, with effects extending to downstream reaches (Keith et al., 2024; Murphy et al., 2019). Reservoir erosion resulting from 2023-2025 deep drawdowns of Green Peter Lake and Lookout Point Lake triggered high turbidity levels that negatively affected public water supply systems for several downstream communities (U.S. Geological Survey, 2026) and caused a large Kokanee (*Oncorhynchus nerka*) mortality event due to barotrauma (Urness, 2023). Additionally, high-volume releases from RO outlets during drawdown operations can cause total dissolved gas supersaturation in downstream reaches, posing additional physiological stressors to fish (Backman and Evans, 2002).

These and other biological, geomorphic, and water-quality effects highlight complex, multi-faceted responses to deep drawdowns and underscore the importance of holistic, a priori evaluation to better anticipate, monitor, and minimize potentially harmful responses to deep drawdowns or other major dam

operations. Reservoirs across the United States are increasingly being operated far outside the conditions for which they were designed, and many regulated rivers are entering a new management era due to shifting hydroclimatic conditions or changing societal values. Even where decades of post-dam operations and associated modeling and monitoring have established a generalized understanding of fluvial thermal regimes (as at Green Peter Lake: Rounds, 2010; Sullivan and Rounds, 2021), a major operational shift like deep drawdown still requires updated models, robust monitoring and a strong mechanistic understanding of energy budgets and reservoir-river coupling. Because every dam, reservoir and river network presents a unique combination of dam infrastructure and operations, reservoir characteristics and downstream river corridor attributes, and because hydroclimatic conditions can vary substantially from year to year, process-based modeling can be used to help understand coupled interactions between the dam operations, reservoir conditions and reservoir releases.

Recognizing that robust, mechanistic models can take years to develop and require many datasets that may not be universally available, a tiered approach could be applied to match the level of monitoring and modeling appropriate for a particular situation. At a minimum, reservoir temperature monitoring data (ideally provided real-time) is essential for understanding reservoir thermal structure and tracking responses to hydroclimatic conditions and dam operations. Combined with records of dam outlet use and timing and downstream temperature monitoring, this foundation could support a general understanding of reservoir temperature dynamics before a fully calibrated mechanistic model is available (Figure 4). Tools such as heat content calculation or a spreadsheet tool from Rounds et al. (2026) can occupy an intermediate tier, using real-time temperature profiles to estimate vertical withdrawal zones and inform outlet blending decisions without requiring a fully calibrated model (S4 Appendix). Development and routine updating of a calibrated mechanistic model could be used to inform real-time operations, predict the effects of proposed operations, and establish threshold conditions to guide adaptive management. Hence, although the models and exact findings of this study can directly inform future implementation of deep drawdowns at Green Peter Lake and other Willamette River Basin reservoirs, the broader modeling

and monitoring approach applied here is likely transferable to other large reservoirs facing similar fish passage and thermal management challenges. Important limitations of this study, including model adjustments for drawdown scenarios, the exclusion of Foster Lake dynamics, and simplified thermal thresholds for assessing biological risk, are in S3 Appendix.

Conclusion

Deep reservoir drawdowns at Green Peter Dam in 2023-25, implemented to facilitate downstream juvenile salmon passage, caused a substantial shift in downstream release temperatures: cooler summer releases but substantially warmer late spring and autumn releases relative to historical conditions. The warmer autumn release temperatures coincided with the adult spawning and early egg incubation period for spring Chinook salmon, and observed temperatures were potentially harmful for spawning fish and their redds. This study demonstrates that two operational strategies can meaningfully reduce peak autumn release temperatures that result from deep reservoir drawdown: (1) exporting near-surface heat through spillway use in late spring and early summer, and (2) delaying deep drawdown initiation to allow for additional seasonal cooling of the epilimnion in late summer and early autumn. The findings and modeling approach used here are directly applicable to future deep drawdown operations at Green Peter Lake and other Willamette River Basin reservoirs and are transferable to large reservoirs elsewhere that are increasingly operated outside of the conditions for which they were designed. More broadly, the thermal consequences documented here illustrate the inherent tradeoffs in managing large dams for multiple objectives, where actions taken to benefit one salmon life stage may inadvertently harm another. This demonstrates the utility of a systems and life-cycle approach to dam management that requires and understanding of and accounts for the close coupling among reservoir thermal conditions, dam operations, downstream release temperatures, and salmon life cycle timing.

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S1 Appendix – Data sources for observed water

temperature, streamflow, and lake elevation data

Time series of water temperature and streamflow data were sourced from USGS streamgages and accessed through the USGS National Water Data for the Nation (U.S. Geological Survey, 2026) via the dataRetrieval package (version 2.7.17; De Cicco et al., (2024)) in R (version 4.4.1; R Core Team, 2024) or via the W2 Animator (version 1.7.1; Rounds, (2026)). Water temperature data from the Middle Santiam River released from Green Peter Dam are from USGS site 14186200 (Middle Santiam River below Green Peter Dam near Foster, OR; U.S. Geological Survey, 2026). Green Peter Lake water surface elevation data prior to 2013 were sourced from the USACE online portal DataQuery 2.0 (U.S. Army Corps of Engineers, 2026); elevation data from 2013 onward were sourced from USGS site 14186100, Green Peter Lake near Foster, OR (U.S. Geological Survey, 2026). Water temperature data from the South Santiam River downstream of Foster Dam are from USGS site 14187200 (South Santiam River near Foster, OR). Foster Lake water surface elevation data prior to 2013 were sourced from the USACE online portal DataQuery 2.0 (U.S. Army Corps of Engineers, 2026); elevation data from 2013 onward were sourced from USGS site 14186600, Foster Lake at Foster, OR (U.S. Geological Survey, 2026). Rule curve elevation data for Green Peter Lake and Foster Lake are from the USACE online portal DataQuery 2.0 (U.S. Army Corps of Engineers, 2026). When data for inflows to Green Peter Lake are provided for additional context, inflow water temperature and discharge data from Quartzville Creek into Green Peter Lake are from USGS site 14185900; Quartzville Creek near Cascadia, OR or inflow water temperature data from the Middle Santiam River into Green Peter Lake are from USGS site 14185800; Middle Santiam River near Cascadia, OR. When data for inflows to Foster Lake are provided for additional context, inflow water temperature data from the South Santiam River into Foster Lake are from USGS site 14185000, South Santiam River below Cascadia, OR (U.S. Geological Survey, 2026).

Floating thermistor data in Green Peter Lake for 2016 and 2023 were sourced from the USACE online portal DataQuery 2.0 (U.S. Army Corps of Engineers, 2026). Floating thermistors were spaced at 0.5, 10, 20, 30, 40, 50, 60, 80, 100, 120, 140, 160, 180, and 200 ft depths. Fixed elevation thermistor data in Green Peter Lake for 2025 were sourced from USACE (N. Buccola, USACE, unpublished data, 2026), with sensors spaced at 10-ft intervals from 770 to 1010 ft elevation. 2025 thermistor string data are available upon request by contacting the U.S. Army Corps of Engineers at DLL-CENWP-Media-Desk@usace.army.mil.

S2 Appendix – Adjustments to CE-QUAL-W2 model parameters for 2023 and drawdown scenarios

In 2023, dam operations at Green Peter Lake included a deep drawdown along with outlet usage and reservoir conditions that differed from operations that were typical prior to 2023. The Green Peter and Foster Lakes model described and documented by Stratton Garvin et al. (2023a) and Stratton Garvin and Rounds (2023) was calibrated under operations of Green Peter and Foster Dams that were typical prior to 2023, and that did not include deep reservoir drawdowns.

After updating model boundary conditions to represent 2023 conditions, but without further modification to model parameters, the previously calibrated and published model (Stratton Garvin et al., 2023a, 2023b) did not adequately capture the thermal structure of the reservoir during the 2023 deep reservoir drawdown period or the timing and magnitude of release temperatures in late summer and autumn. As a result, several model input parameters were adjusted to better capture in-reservoir temperatures in Green Peter Lake and the release temperatures downstream of Green Peter and Foster Dams during the deep reservoir drawdown operation.

925 Model parameter and data-source adjustments

926 Relative to the previously documented models, the sources for wind and precipitation data were changed,
927 and the method used to estimate Middle Santiam River inflows was updated. Adjustments also were
928 made to the model light extinction coefficients and the model outlet type and outlet line-width parameters
929 based on in-reservoir turbidity conditions and comparisons of model results to downstream and in-
930 reservoir temperature validation data. These data-source changes and parameter adjustments resulted in a
931 model that was not calibrated across multiple years but provided a better fit to the measured conditions in
932 2023. Further adjustments to model parameters or inputs could be made to improve the comparison of
933 model results to measured calibration data, but adjustments were minimized to avoid over-fitting the
934 model, given that only one summer of deep drawdown data were available at that time to provide
935 feedback for calibration.

936 Wind speed

937 The wind speed and direction time-series data source was changed from the Eugene Airport site (Mahlon
938 Sweet Field, WBAN 24221) in the original calibrated model to the Remote Automated Weather Station
939 (RAWS) site in Jordan, Oregon for the modified 2023 model (Western Regional Climate Center, 2024).
940 The calibrated model did not accurately capture thermal stratification using the wind-speed data from the
941 Eugene Airport because those wind speeds generally were too high, causing too much surface mixing and
942 a deepening of the extent of the simulated epilimnion in Green Peter Lake during summer. This was
943 causing warm water from the bottom of the epilimnion to be pulled down and released through the lower
944 model outlets too soon, resulting in an increase in modeled downstream release temperatures several
945 weeks earlier than observed in late summer of 2023. Changing the wind speed data source to the Jordan
946 RAWS station resulted in a better representation of the thermal structure and timing of release
947 temperatures from Green Peter Dam. The Jordan RAWS data had been used in some previously published
948 CE-QUAL-W2 models of the Willamette Valley System (Stratton Garvin and others, 2023).

949 Light extinction coefficient

950 The deep drawdown operations in 2023 caused a substantial increase in turbidity in both Green Peter and
951 Foster Lakes during late summer and autumn of 2023, which decreased the transmittance of light and heat
952 to deeper depths of the water column. To account for this, the light extinction coefficient in the model for
953 both lakes was increased linearly during the drawdown period, beginning when Green Peter Lake was
954 first drawn down below minimum conservation pool and reaching a maximum value on November 4th
955 when the Middle Santiam River turbidity levels measured below Green Peter Dam at USGS site
956 14186200 (U.S. Geological Survey, 2026) were at their highest level of the 2023 drawdown period. The
957 imposed light extinction coefficient was then decreased linearly back to its original calibrated value from
958 November 4 through the end of the year. The light extinction coefficient could be adjusted with higher
959 precision and accuracy using more detailed in-reservoir turbidity data if such data were available, but this
960 general approach was deemed adequate for the purpose of the model.

961 Outlet source type and line width

962 During the deep drawdown in 2023, the power penstock and regulating outlet (RO) were used to rapidly
963 lower the lake water-surface elevation. The extent of the vertical withdrawal zone, or vertical envelope
964 from which water is pulled toward a dam outlet, affects the vertical position of the thermocline and the
965 temperature of water released from the outlet. If the vertical withdrawal zone is not accurately represented
966 in the model, an inaccurate representation of the reservoir thermal structure and the outlet release
967 temperatures is likely. To better match the measured release temperatures from Green Peter Dam, the
968 power penstock and RO structures were changed in the model from point sinks to line sinks, and line
969 widths were assigned and adjusted based on a comparison of model results to measured calibration data.
970 (The RO was not used as part of typical dam operations prior to 2023.)

971 Precipitation boundary condition data source

972 The precipitation time-series data source was changed because the data source documented and used by
973 Stratton Garvin and others (2023) was not available for 2023. Time series of precipitation rate data for the
974 2023 model were sourced from the USGS Foster Dam Meteorological Station near Foster, OR (USGS site
975 442451122402200; U.S. Geological Survey, 2026) and converted from inches per 15 minutes to meters
976 per second (cubic meters per square meter per second) at 15-minute time steps.

977 Middle Santiam River flow boundary condition

978 The Middle Santiam River inflow estimation method was changed to a watershed area method, where the
979 ratios of drainage areas of the Middle Santiam River and Quartzville Creek were used to estimate
980 streamflow, based on measured data from USGS site 14185900 (U.S. Geological Survey, 2026). As of the
981 summer of 2023, a new USGS streamflow gage was installed on the Middle Santiam River upstream of
982 Green Peter Lake (USGS site 14185600) (U.S. Geological Survey, 2026) and data from that site could be
983 used to increase the accuracy of inflow estimates.

984 Model Fit

985 Water temperature results from the 2023 adjusted model were evaluated by (1) comparing modeled
986 temperatures to those measured from floating thermistor strings in Green Peter Lake, (2) comparing
987 modeled release temperature from Green Peter Dam to measurements at USGS site 14186200 (Middle
988 Santiam River below Green Peter Dam near Foster, OR; U.S. Geological Survey, 2026), and (3)
989 comparing modeled release temperature from Foster Dam to measurements at USGS site 14187200
990 (South Santiam River near Foster, OR; U.S. Geological Survey, 2026).

991 Time series of release temperatures from Green Peter Lake indicate that during spring and late autumn the
992 model underestimated release temperatures, whereas the model slightly overestimated release
993 temperatures during late summer and early autumn when the reservoir was actively being drawn down.

The subdaily mean absolute error (MAE) for Green Peter Dam modeled release temperatures was 0.77 °C.

Time series of temperature profiles in Green Peter Lake indicate that during spring at all depths the model underestimated reservoir temperatures. The model slightly overestimated temperatures during summer through early autumn at all depths, and slightly underestimated reservoir temperatures later in autumn at all depths. The Green Peter Lake thermistor data were incomplete and did not include temperature data for any depths from April 10 through June 8, 2023. Therefore, this period could not be evaluated. Additionally, once the deep drawdown began, data were only available for a subset of the temperature string sensors through the remainder of the year, and these data were used to assess model fit during this period. Overall, subdaily MAE values for reservoir temperatures were less than 1.0 °C at most depths, except at 9.1 m and 12.2 m where the MAE was 1.2 °C.

Time series of release temperatures from Foster Lake indicate that during spring and early summer the model underestimated release temperatures. The model overestimated release temperatures from mid-June through July. The subdaily MAE for Foster modeled release temperatures was 0.80 °C. Temperature models often are considered to produce acceptable results if comparisons of model predictions to measured data produces an MAE of less than 1 °C. Regardless, the modified model for 2023 seemed to produce useful predictions of the thickness of the epilimnion, the position of the thermocline, and the timing of warmer release temperatures from Green Peter Dam during the late summer through autumn time period, and the model results were sufficient to provide insights into the processes driving those conditions.

S3 Appendix - Limitations

The 2023 CE-QUAL-W2 model of Green Peter and Foster Lakes was based on a modification of the calibrated 2016 model (Stratton Garvin et al., 2023a) for conditions that occurred in 2023, but the model

was not fully calibrated or validated for drawdown operations (refer to S2 Appendix for additional information about parameter adjustments and model fit). The model and results are therefore appropriate for comparing operational scenarios and understanding relative differences in release temperatures under different drawdown timing schedules rather than for making absolute temperature predictions; the latter will have higher associated uncertainties. Comparisons between 2016 and 2023 were based on observed data where possible, and model results were primarily used to better illustrate and understand the in-reservoir and operational processes driving reservoir temperature dynamics and release temperatures.

The drawdown timing scenarios evaluated in this study were based on the specific reservoir conditions, hydroclimatic conditions, and authorized purposes of Green Peter and Foster Dams that existed in this study. Findings regarding the relative thermal tradeoffs of early versus delayed deep drawdowns are therefore most directly applicable to similar conditions and operational contexts. For example, an earlier deep drawdown in a drier year than modeled in these scenarios could produce different tradeoffs than those described here. Additional scenario modeling under a broader range of hydroclimatic conditions and operational constraints would help clarify the extent to which the tradeoffs identified here generalize beyond the specific conditions evaluated in this study.

Although previous work documented that Green Peter Dam operations exert a greater influence than Foster Dam operations on release temperatures to the South Santiam River (Sullivan and Rounds, 2021), release temperatures from Green Peter Dam are further modified by Foster Lake residence time and Foster Dam operations. Conditions within Foster Lake during a deep drawdown of Green Peter Lake were not evaluated here, and a better understanding of these dynamics could further inform optimal operations at both facilities. Finally, while a comparison of Green Peter Dam and Foster Dam release temperatures with T_{crit} thresholds in autumn provides a general indication of potentially stressful thermal conditions for spring Chinook salmon during the spawning and early egg incubation period, threshold comparisons alone do not fully characterize the biological implications of those temperatures for salmon or other cold-water adapted fish.

S4 Appendix – Example of a tractable approach for implementing extended spillway use and delayed deep drawdown initiation to reduce maximum autumn release temperatures

A tractable approach for implementing extended spillway use and delayed deep drawdown initiation at Green Peter Dam as part of an overall adaptive management plan could entail the following strategies alongside other considerations regarding fish passage and constraints on outlet usage. First, spillway use could be prioritized beginning in spring and continuing as long as possible into summer to export near-surface heat from the lake to minimize epilimnion heat accumulation and thickness. Maintaining access to the spillway, however, requires maintaining sufficiently high pool levels to enable spillway releases, which can be challenging in summer months when reservoir outflows typically exceed inflows. Managers would therefore need to balance tradeoffs between maintaining high pool levels to preserve spillway access and satisfying downstream flow requirements for water users and fisheries. In addition, epilimnetic water released through the spillway during the summer may itself exceed acceptable temperature thresholds for downstream salmon, making it necessary to blend cooler water from lower outlets. When such blending is needed, releases from lower outlets could be made judiciously to conserve hypolimnetic volume when possible for use later in the drawdown. Computational tools that facilitate real-time decision-making, such as a spreadsheet tool developed by Rounds et al., (2026), can be used to help inform release rates from each outlet. Provided with thermal profiles characterizing reservoir thermal structure, the tool estimates the vertical withdrawal zone associated with specified outflows and dam outlets and calculates release temperatures, thereby enabling managers to determine the proportion of

power penstock or RO water that must be blended into a spillway release to maintain safe release temperatures.

Second, delaying drawdown initiation is critical to allow natural cooling of the reservoir to occur, with exact timing dictated by reservoir thermal conditions. While waiting for natural cooling to occur, lake levels could be maintained as high as feasible, and releases from lower outlets could be limited, thereby keeping the water surface elevation and thermocline above the outlet elevations, and preserving access to hypolimnetic water while epilimnetic heat is released to the environment. One approach to help inform the timing of deep drawdown initiation could be to calculate the total heat content (and average temperature) of the reservoir at the time of drawdown initiation, derived from measured temperature profiles and reservoir volume. This quantity would help managers to better anticipate maximum release temperatures that may be expected once the drawdown begins, given that the deep drawdown might also contribute to complete vertical mixing of the lake during the period when maximum release temperatures occurs.

If, despite these efforts, reservoir conditions at the time of drawdown initiation still indicate release temperatures that are too high, managers could attempt to initiate the drawdown through the power penstock and then monitor rising release temperatures and reservoir thermal structure in real time, watching in particular for a sharp rise in release temperatures from the power penstock, which would indicate that the withdrawal zone has begun entraining warmer water from near the thermocline. If operations allow, rather than transitioning to the RO all at once, managers could then blend in RO water gradually and only as needed to blunt the emerging peak temperatures, preserving the remaining cool water for as long as possible rather than depleting it prematurely. Again, computational tools (such as the spreadsheet tool by Rounds et al., [2026]) would enable managers to more precisely determine how much water to blend from the RO with releases from the power penstock so as to decrease total release temperatures, while avoiding unnecessarily large withdrawal zones and minimizing warm-water entrainment from near the thermocline. This approach can help managers determine the timing and

1088 volume of lower-outlet releases needed to reduce peak release temperatures while also preserving
1089 stratification for as long as possible into autumn, which (although not evaluated in this study) provides an
1090 additional benefit of retaining cool water in the reservoir where juvenile Chinook can seek thermal refuge
1091 while waiting for downstream passage conditions provided by the deep drawdown. Resource managers
1092 should consider the role of downstream reservoirs prior to implementing the described possible strategies;
1093 in the case of Green Peter Dam, Foster Dam immediately downstream further influences release
1094 temperatures; therefore, additional analysis into the thermal effects of downstream reservoirs like Foster
1095 Lake would be needed.

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