# Thermal Regime of the Columbia River at Lake Roosevelt


**U.S. Department of the Interior**
**Bureau of Reclamation**
**Pacific Northwest Regional Office**
**Boise, Idaho**



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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

# Acronyms and Abbreviations

| | |
|---|---|
| BiOp | Biological Opinion |
| CBP | Columbia Basin Project |
| cfs | cubic feet per second |
| CRB | Columbia River Basin |
| CWA | Clean Water Act |
| ESA | Endangered Species Act |
| FCRPS | Federal Columbia River Power System |
| FELCC | Firm Energy Load Carrying Capacity |
| FRM | flood risk management |
| JWKIII P/G | John W. Keys III pump/generating |
| kV | kilovolt |
| LRISRP | Lake Roosevelt Incremental Storage Release Program |
| M&I | municipal and industrial |
| MAF | million acre-feet |
| MW | megawatt |
| NOAA Fisheries | National Oceanic and Atmospheric Administration National Marine Fisheries Service |
| PUD | public utility district |
| Reclamation | Bureau of Reclamation |
| RM | river mile |
| RT | retention time |
| TDG | total dissolved gas |
| TPP | Third Power Plant |
| USACE | U.S. Army Corps of Engineers |

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# EXECUTIVE SUMMARY

Warm water events that affect anadromous and other fish species, as experienced in the summer of 2015, highlight the need for fish managers and water managers to investigate potential actions that would reduce water temperatures and risk to migrating fish. These events raise questions on how dams, such as Grand Coulee, could be operated differently to help mitigate rising water temperatures. Storage reservoirs that behave like lakes can mitigate increasing temperatures and develop strong thermal stratification with cold water at depth. Others, like Franklin D. Roosevelt Reservoir (commonly referred to as Lake Roosevelt), have run-of-river thermal characteristics due to the very high volume of flow passing through the reservoir in a relatively short period of time; therefore, the thermal stratification is weak and temperatures are similar throughout the water column. Within this framework, Reclamation examined the current potential for Grand Coulee to reduce downstream temperatures during warm summer river conditions. This paper focuses specifically on the thermal regime of the Columbia River above and below Lake Roosevelt, thermal stratification of the reservoir, the residence time of water in the reservoir, and the current operations of Grand Coulee Dam.

Key concepts discussed in this paper include:

1. **Weak Stratification –** Relatively short retention times in Lake Roosevelt (ranging from 36 days on average in June to 76 days on average in September) present a key limiting factor for stratification (temperature variation at depth). The reservoir exhibits only shallow and weak stratification during the summer months, with the largest temperature gradients occurring near the surface. Much stronger stratification would be necessary for meaningful thermal mitigation for the lower Columbia River from Grand Coulee operations.

2. **Operational Flexibility –** There is limited flexibility to change operations between power plants (i.e., release water from different depths in the reservoir). The intakes for the Left and Right Power Plants are located 100 feet deeper (at approximately 1,040 feet elevation) in the reservoir than the intakes for the Third Power Plant (at approximately 1,140 feet elevation). However, this difference in elevation cannot be leveraged to influence downstream water temperature because the units in the Left and Right Power Plants are operated continuously while the units in the Third Power Plant are cycled on and off for peaking operations. Because the lower Left and Right Power Plants are operated continuously, current operations release the coolest water possible in the summer.

3. **Outflow temperatures from Grand Coulee Dam –** Outflowing water temperatures are a result of the inflowing water temperatures, local climate, thermal stratification in the reservoir, and dam operations.

In summary, due to weak or shallow stratification with the largest temperature differences near the surface and current operational configuration, Grand Coulee Dam currently releases the coolest water possible during the summer months.  Grand Coulee Dam has limited potential to mitigate for downstream temperatures due to a combination of higher summer reservoir temperatures, weak thermal stratification during summer, and operational and structural constraints.

# 1 INTRODUCTION

Water temperature regimes are important to the timing and survival of salmon and steelhead migrating through the Columbia River Basin. Water temperature in an ongoing issue in the Columbia River. For several years fish managers have been contemplating the role Grand Coulee Dam and Lake Roosevelt could play in reducing downstream temperatures for fish. In 2015, record-high mainstem water temperatures resulted in heavy losses to the Snake and Columbia rivers sockeye runs. This event renewed the interest in Grand Coulee as a tool to mitigate for water temperatures. Warm water events that affect anadromous fish species highlight the need for fish managers and water managers to investigate potential actions that would reduce water temperatures and thus reduce risk to migrating fish.

Storage reservoirs can influence water temperature by changing travel time, causing stratification, and increasing surface area exposed to solar radiation. Some dams are equipped with the ability to release water from varying elevations that allow operators to manipulate downstream water temperatures by drawing from specific stratified layers. Often these capabilities, referred to as selective withdrawal, are used to release warmer waters from the surface of the reservoir.

Franklin D. Roosevelt Reservoir (commonly referred to as Lake Roosevelt) behind Grand Coulee Dam is a large storage reservoir (5.2 million acre-feet [MAF] active space, 9.4 MAF total space) and is considered by some as a potential source of cool stratified water for the Columbia River; however, it lacks stratification and often responds more like a run-of-river project.

This paper summarizes the thermal data collected to date and further examines and explains the thermal conditions of the Columbia River at Grand Coulee Dam. The summary of the thermal regime includes inflowing and outflowing temperatures, water residence time in the reservoir, and the resulting thermal stratification in the reservoir pool. The data includes temperatures collected near the dam (see Appendix A) that were used to document the thermal stratification of Lake Roosevelt. In addition, the operations and configuration of Grand Coulee were examined to provide context to operational opportunity and constraints. To contrast the thermal conditions of Lake Roosevelt, Reclamation compares stratification conditions with Dworshak Reservoir, which is known to use operations to assist in mitigating[1] temperatures in the lower Snake River. This paper demonstrates that, although a large storage reservoir, Grand Coulee Dam behaves differently than Dworshak and does not offer potential to provide similar thermal mitigation to the Columbia River.

[1] Temperature mitigation can either be adding cool or warm water to the river to impact downstream temperatures.

# 2 LAKE ROOSEVELT AND GRAND COULEE DAM

## 2.1 Setting and Project Description

Grand Coulee Dam is located on the Columbia River at approximately river mile (RM) 597. It is the primary component of the Reclamation's Columbia Basin Project (CBP), which was developed to provide flood risk management (FRM), irrigation, municipal, and industrial (M&I) water supply, and hydropower generation. Grand Coulee is the largest dam in the Columbia River Basin, comprised of 12-million cubic yards of concrete, and measuring 550 feet tall and 5,223 feet long (Figure 2-1). The reservoir impounded by Grand Coulee Dam is Franklin D. Roosevelt Lake (Lake Roosevelt), named for the president who authorized construction of the dam. Lake Roosevelt extends 151 miles upstream to the U.S.-Canadian border. Grand Coulee Dam is one of 14 federal dams in the Columbia River System (Figure 2-2). These projects are operated in a coordinated fashion to provide FRM, power, water supply, benefits to resident and anadromous endangered species, recreation, navigation, and other purposes. Downstream of Grand Coulee the Columbia River flows through Lake Rufus Woods (behind Chief Joseph Dam), multiple public utility district (PUD) run-of-river dams (operated by 3 different PUD's), and into McNary pool at the confluence with the Snake River. Downstream of the confluence of the Snake River, on the lower Columbia River are four federal run-of-river dams, owned and operated by the U.S. Army Corps of Engineers (USACE): McNary, John Day, The Dalles, and Bonneville dams (in order from upstream to downstream).

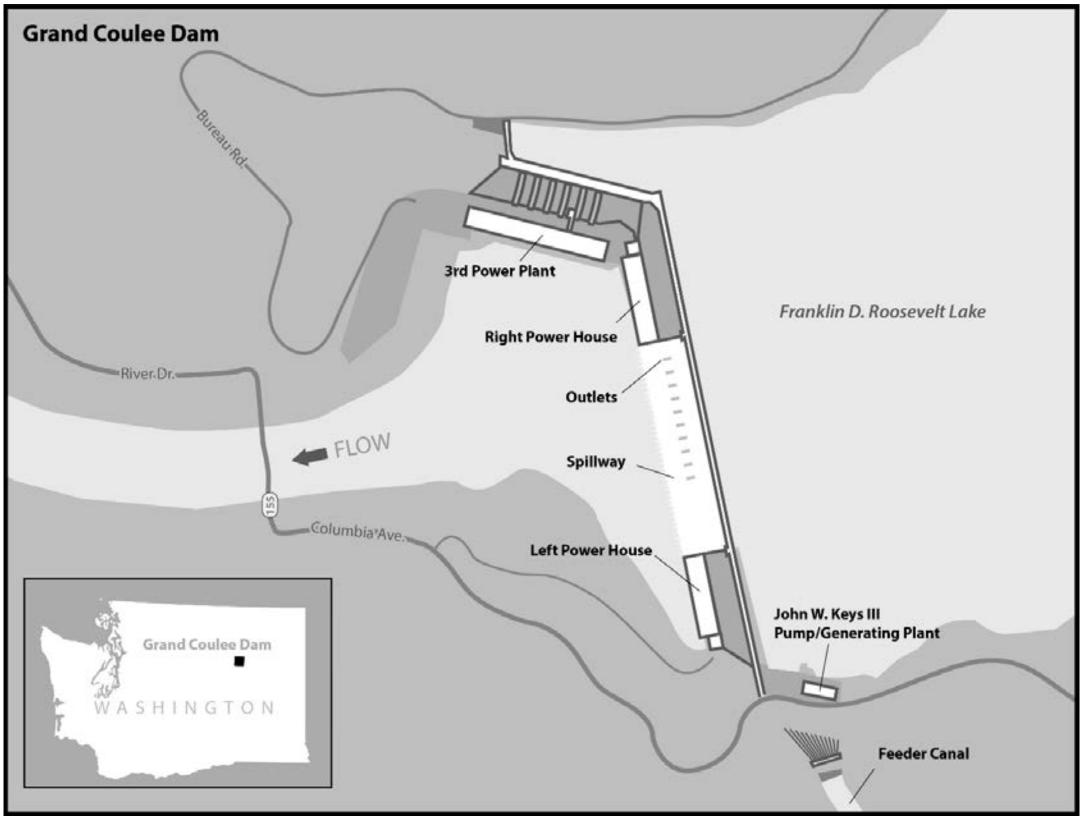


**Figure 2-1. Overview diagram of Grand Coulee Dam and key features.**


**Figure 2-2. Location of Grand Coulee Dam on the Columbia River.**

Reclamation has been authorized by Congress to operate Grand Coulee Dam for the multiple purposes of FRM, navigation, power generation, and irrigation. In coordination with other Federal Columbia River Power System (FCRPS) facilities, Reclamation operates the dam to respond to a variety of factors including water supply conditions, power demand, and fish flows. These factors change from month-to-month and season-to-season.

Grand Coulee Dam generates power primarily through the Left, Right, and Third Power Plants (Figure 2-1). There is a significant difference between the capacity of the units in the Third Power Plant (approximately 30,000 cubic feet per second [cfs] and 800 megawatts [MW] per unit) and those in the Left and Right Power Plants (approximately 6,000 cfs and 150 MW per unit). Table 2-1 shows that it would take five units from the Left and/or Right Power Plants to equal the hydraulic capacity of one unit from the Third Powerhouse. This disparity limits the flexibility to shift operations from the Left and Right to the Third Power Plant or vice versa.

The John W. Keys III pump/generating (JWKIII P/G) plant pumps water from Lake Roosevelt to Banks Lake through six pumps and six pump-generators to supply water to the CBP for irrigation and M&I. JWKIII P/G can also be used to generate power by running water from Banks Lake to Lake Roosevelt through the six pump/generating units.

**Table 2-1. Powerplant summary of hydraulic capacity and intake elevation. This is the full capacity; actual operations are limited by maintenance outages and power demand.**

| Powerplant | Approximate Intake Elevation (feet) | Approximate Powerplant Hydraulic Capacity per unit (kcf) | Approximate Powerplant Capacity per unit (MW) | Approximate Total Powerplant Hydraulic Capacity (kcfs)[a] | Approximate Total Powerplant Capacity (MW)[a] |
|---|---|---|---|---|---|
| Third (6 units) | 1140 | 30 | 805/690 | 120 | 4,485 |
| Left (9 units) | 1040 | 6 | 125 | 42 | 1,125 |
| Right (9 units) | 1040 | 6 | 125 | 42 | 1,125 |
| [a] Assuming outages of 2 units in each powerplant for maintenance. | | | | | |

## 2.2 Temperature Regimes and Stratification

To understand the thermal regime of Lake Roosevelt, Reclamation has collected routine measurements of the reservoir thermal profile near the dam since 2000. Additionally, Reclamation has developed a two-dimensional[2] (longitudinal-vertical) water quality model to better understand Grand Coulee operations and resulting effects on downstream Columbia River temperatures and total dissolved gas (TDG). This model could be a useful tool in the future.

### 2.2.1 Temperatures above and below Grand Coulee

Grand Coulee Dam is a large structure that influences the flow of the Columbia River. The source for Columbia River data in and around Lake Roosevelt is summarized in Table 2-2.

[2] http://www.ce.pdx.edu/w2/, for more information about CE-QUAL-W2, the water quality model developed for Lake Roosevelt.

**Table 2-2. Columbia River and Lake Roosevelt temperature sources.**

| Site Name | Note | Source |
|---|---|---|
| USGS 12399500 Columbia River at International Boundary | Columbia River upstream of Lake Roosevelt. | U.S. Geological Survey (USGS) |
| Columbia River at Barry, Below Grand Coulee Dam, WA | Columbia River downstream of Grand Coulee Dam. | Reclamation |
| USGS 12514400 Columbia River below HWY 395 Bridge at Pasco, WA | Columbia River temperature downstream of middle-Columbia private dams and upstream of Snake River confluence. | USGS |
| Lake Roosevelt Thermal Stratification Data | This thermistor string is located at the log-boom near the dam (Appendix A). | Reclamation |

Median temperatures below Grand Coulee Dam generally range from a low of about 3 degrees Celsius (ºC) during the winter to a high of about 19ºC by the end of summer (Figure 2-3).

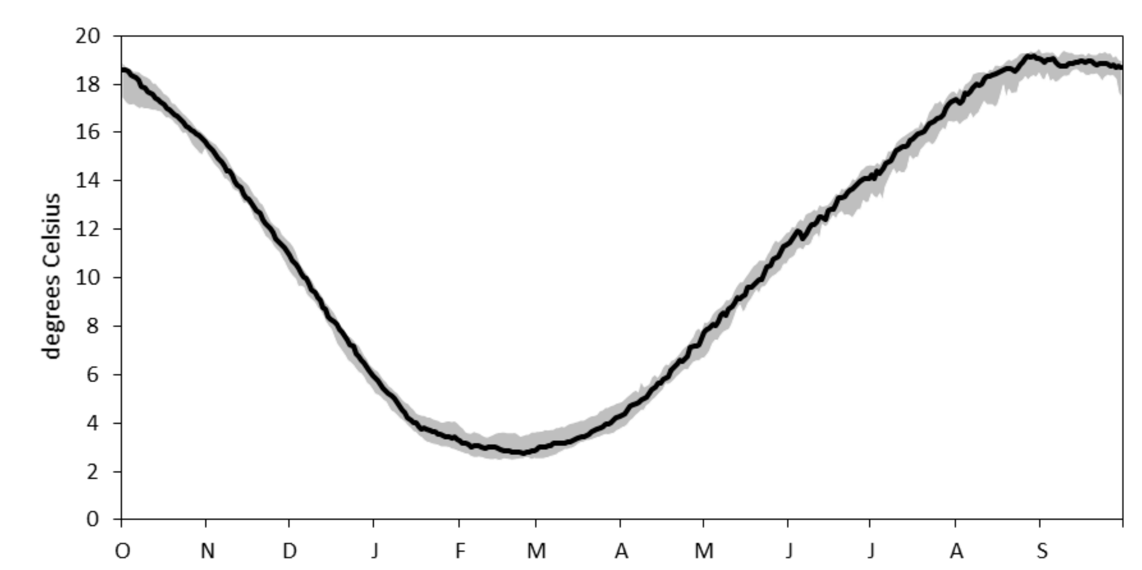


**Figure 2-3. Water temperatures measured downstream of Grand Coulee Dam, showing the median, 20 percent, and 80 percent exceedance temperatures for water years 2000 through 2015.**

Compared to inflow temperatures at the International Boundary, Grand Coulee releases tend to be warmer from October through January as these temperatures steadily cool through this period. For example, the median temperature coming out of Grand Coulee Dam in October is approximately 17°C whereas the inflowing temperatures at the International Boundary are approximately 12°C. In January, the median water temperatures downstream of Grand Coulee Dam (4°C) and at the International Boundary (3.5°C) are almost the same. Temperatures on the Columbia River upstream and downstream of Grand Coulee Dam reach their lows in late February to early March, and on median are in the range of 3°C. In the spring, the Columbia River temperatures warm, to approximately 6°C in April 9 to 10°C in May, and 13°C in June at both the International Boundary and downstream of Grand Coulee. July and August temperatures in the lower river are important to migrating anadromous fish. In July and early August, the temperatures below Grand Coulee Dam are lower than inflowing temperatures, at the International Boundary. For example, in July, the river temperature downstream of Grand Coulee is approximately 15.5°C on average, which is cooler than inflowing temperatures for this period at an average of 17°C at the International Boundary. These patterns are exhibited in Figure 2-4. Table 2-3 also exhibits these patterns and temperatures in the Clearwater River and is included for comparison.

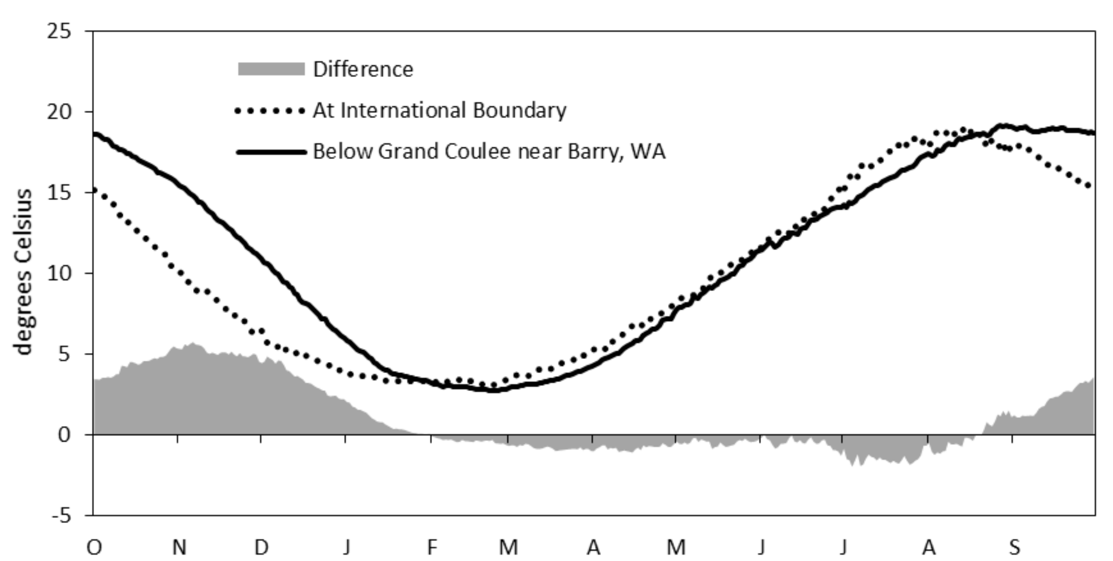


**Figure 2-4. Median Columbia River water temperatures measured at the International Boundary and below Grand Coulee Dam near Barry, Washington for water years 2000 through 2015.**

**Table 2-3. Median monthly river temperatures (in degrees Celsius) of the Columbia River at the International Boundary (USGS 12399500); near Barry, WA (USBR); Pasco, WA (USGS 12514400) and Clearwater River at Spalding, ID (USGS 13342500). The Clearwater River at Spalding, ID data are for comparison purposes discussed further in Section 2.3.5**

| | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Columbia River at International Boundary | 13 | 8 | 5 | 3 | 3 | 4 | 7 | 10 | 13 | 17 | 18 | 16 |
| Columbia River nr Barry, WA | 17 | 13 | 8 | 4 | 3 | 4 | 6 | 9 | 13 | 16 | 18 | 19 |
| Columbia River at Pasco, WA | 17 | na | na | na | na | 5 | 8 | 12 | 15 | 18 | 20 | 19 |
| Clearwater River at Spalding, ID | 11 | 7 | 4 | 3 | 4 | 6 | 7 | 9 | 12 | 13 | 12 | 13 |

Downstream of Grand Coulee Dam the Columbia River flows through Lake Rufus Woods, the reservoir behind the USACE' Chief Joseph Dam; and then flows through five run-of-river PUD projects (Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids). Presumable fall and winter temperatures are very similar from below Grand Coulee Dam to below Priest Rapids Dam near Pasco, Washington (upstream of the confluence with the Snake River). Data are limited at Pasco, Washington in the fall and winter. During late spring through the summer (May through August) the temperature increases approximately 2ºC from Grand Coulee Dam Pasco, Washington (Table 2-3). These increases result in median temperatures in the Columbia River at Pasco, Washington of 12°C in May climbing to 20°C in August. In late August and early September temperatures in Lake Roosevelt are at their annual peak, and atmospheric conditions are such that water actual cools as it travels downstream. This condition likely holds until the reservoir becomes more isothermal in October as described below.

## 2.2.2 Reservoir Stratification

### 2.2.2.1 Lake Roosevelt

Lake Roosevelt behaves somewhere between a river (riverine) and a lake (lacustrine); the hydrologic reasons for this are further examined in 2.2.3. During the spring and early-summer, the reservoir warms and weakly stratifies with the development of a warm shallow layer (the epilimnion) in the top 20 to 50 feet (e.g., Figure 2-5 shows the stratification for water year 2009). The penstocks (or water intake structures) to each of the power plants are located below the epilimnion, where the temperature gradient exhibits only a small decrease in temperature with depth during the summer. Figure 2-6 illustrates the difference in temperature between the two penstock intakes over time (see Appendix A for additional examples of temperature differences between the two powerplant intakes). The maximum temperature difference between the penstock elevation of the Left and Right Power Plants (located at elevation 1,040 feet) and the penstock elevation of the Third Power Plant (located at elevation 1,140 feet) is normally 1 to 2ºC during June and July (see Table 2-4).  This temperature difference is insufficient to provide cooler water to the lower Columbia River with the operational constraints at Grand Coulee Dam and the general warming through the mid-Columbia reach that is affected by a series of PUD hydropower projects.

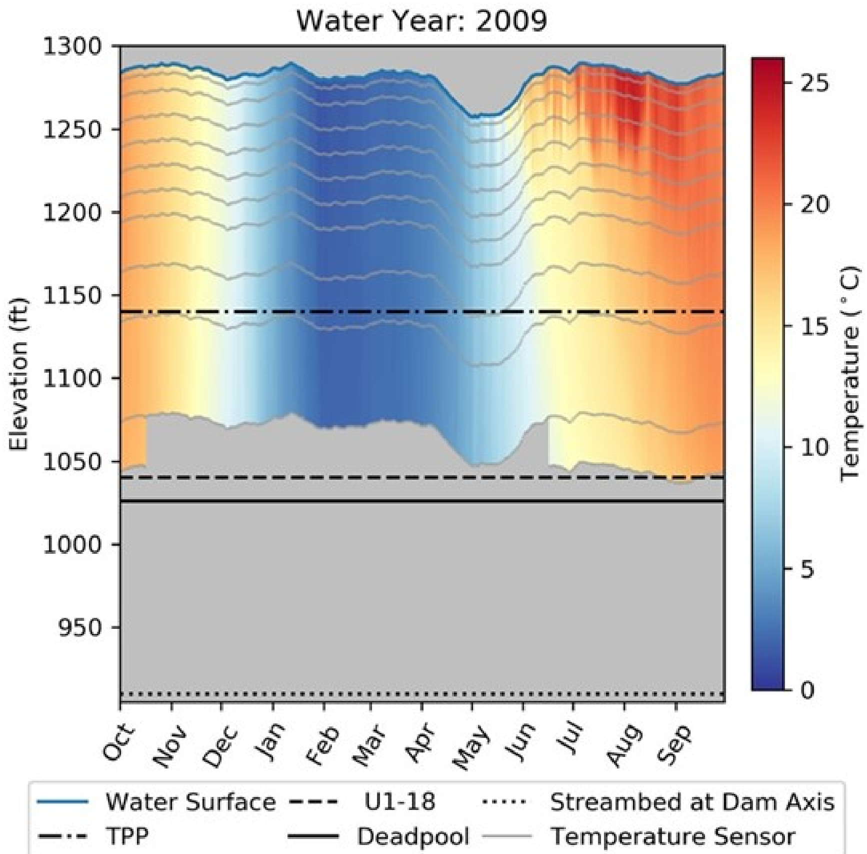


**Figure 2-5. Thermal stratification of Lake Roosevelt, water year 2009 is presented here as an example of the thermal characteristic near the dam because it has a complete year of data available.  TPP is the Third Power Plant; U1-18 are the units of the Left and Right Power Plants.**

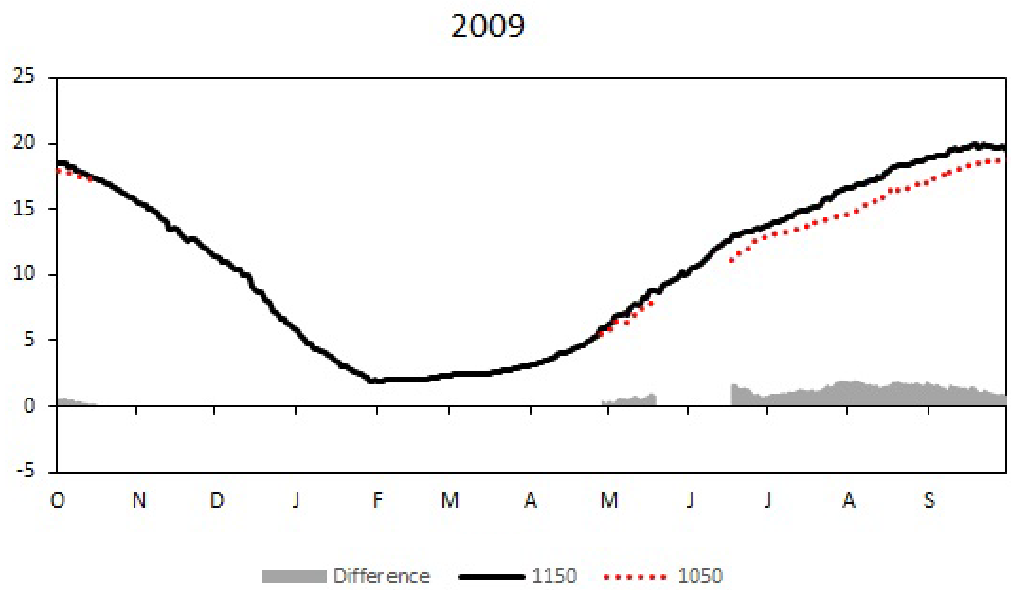


**Figure 2-6. Comparison of water temperatures in Lake Roosevelt during water year 2009, at 1150 feet and 1050 feet elevation. These elevations approximate the power plant intakes for the Third Power Plant (1,150 feet), and the Left and Right Power plants (1,050 feet). Note that data gaps exist due to data collection issues.**

**Table 2-4. Monthly average temperature difference between reservoir temperatures between 1,150 feet (approximate elevation of TPP) and 1050 feet (approximate elevation of the Left and Right Power plants). Data missing in tables reflects data gaps, typically at lower elevation thermistor.**

| | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2000** | 0.2 | 0.3 | 0.1 | 0.1 | 0.0 | 0.1 | 0.2 | 0.1 | 0.6 | 1.2 | 1.8 | 0.5 |
| **2001** | 0.5 | 0.5 | 0.4 | 0.0 | -0.1 | 0.0 | 0.3 | | 1.2 | 1.5 | 3.5 | 1.4 |
| **2002** | 0.2 | 0.5 | | | | | | | 1.7 | 2.1 | 1.8 | 0.5 |
| **2003** | 0.2 | 0.4 | 0.3 | 0.1 | 0.1 | 0.0 | 0.4 | 1.1 | 1.8 | 1.7 | 2.1 | 0.7 |
| **2004** | 0.4 | 0.3 | 0.4 | 0.0 | | 0.0 | | 1.5 | 1.0 | 1.5 | 2.6 | 0.7 |
| **2005** | 0.4 | 0.3 | 0.4 | 0.0 | -0.1 | 0.0 | | | 1.2 | 1.1 | 1.3 | 0.6 |
| **2006** | 0.3 | | | | | | | 0.3 | | 1.7 | 1.6 | 0.4 |
| **2007** | 0.6 | | | | | | | | | | | |
| **2008** | 0.4 | 0.7 | 0.5 | 0.1 | -0.1 | 0.0 | 0.2 | 0.4 | 0.4 | 2.0 | 1.5 | 0.8 |
| **2009** | 0.4 | | | | | | 0.4 | 0.7 | 1.2 | 1.3 | 1.8 | 1.3 |
| **2010** | 0.4 | | | | | | | 1.1 | | 1.7 | 1.1 | 1.1 |
| **2011** | 0.7 | | | | | 0.0 | 0.1 | 0.2 | 0.1 | 0.7 | 0.9 | 1.0 |
| **2012** | 0.2 | | | | | 0.0 | 0.1 | 0.2 | 0.1 | | | |
| **2013** | 0.2 | | | | | | | | | 1.4 | 1.3 | 0.7 |
| **2014** | 0.3 | | | | | 0.0 | 0.2 | 0.4 | 0.5 | 1.1 | 1.1 | 0.4 |
| **2015** | 0.3 | | | | | 0.0 | 0.2 | 1.2 | 1.2 | 0.9 | 0.3 | 0.4 |
| **2016** | | | | | | 0.1 | 0.5 | 0.7 | | | | |
| **Average** | **0.4** | **0.4** | **0.4** | **0.0** | **0.0** | **0.0** | **0.3** | **0.6** | **0.9** | **1.4** | **1.6** | **0.8** |
| **Max** | 0.7 | 0.7 | 0.5 | 0.1 | 0.1 | 0.1 | 0.5 | 1.5 | 1.8 | 2.1 | 3.5 | 1.4 |

### 2.2.3 Reservoir Retention Time

The retention time (RT) of a reservoir is the average time a water molecule will spend in that reservoir. RT is a theoretical value calculated as the ratio of reservoir volume to average flow (either inflow or outflow). The RT in a reservoir or lake is important because it influences several lake and reservoir behaviors including stratification (increasing with increasing retention time) and retention of nutrients (Straškraba 1999). When RT is short the entire reservoir could become a riverine zone; when the RT is long it can be a more lacustrine (lake) zone (Straškraba 1999). The RT influences both the longitudinal and vertical patterns observed in a reservoir and is the most useful variable for prediction of stratification (Straškraba 1999).

The heat gain by a reservoir can typically be divided into two components, the advective flow of water and energy (temperature) from upstream and the net gain of energy (temperature) from solar radiation on the reservoir. The RT controls the significance of the advective source of heat, with shorter RT corresponding to increased influence of advective heat gain or loss.

#### 2.2.3.1 Grand Coulee and Lake Roosevelt

Even though Lake Roosevelt is a rather large storage project, the reservoir does not exhibit prominent stratified conditions like other large storage reservoirs (Appendix A). This can be partially explained by Lake Roosevelt's relatively short RT (Figure 2-7), following the assumption that longer residence time allows greater thermal stratification because the water body behaves more like a lake.

Inflows into Lake Roosevelt are generally large enough that the entire capacity (9.4 MAF) can be refilled seven or eight times each year (average annual flow at Grand Coulee Dam is 77 MAF, or about 106,000 cfs). In dry years (e.g., 2001), there is generally enough flow to completely refill the reservoir approximately 6 times, while in wet years (i.e., 1997), there is generally enough water for this to occur 11 times.

Using the ratio of storage volume to flow rate as an indicator of average residence time in Lake Roosevelt, the monthly average residence time varies from 36 days in June to 76 days in September.

In summary, the RT for Lake Roosevelt results in more riverine circulation and therefore, strong thermal stratification does not set up during warm summer months.

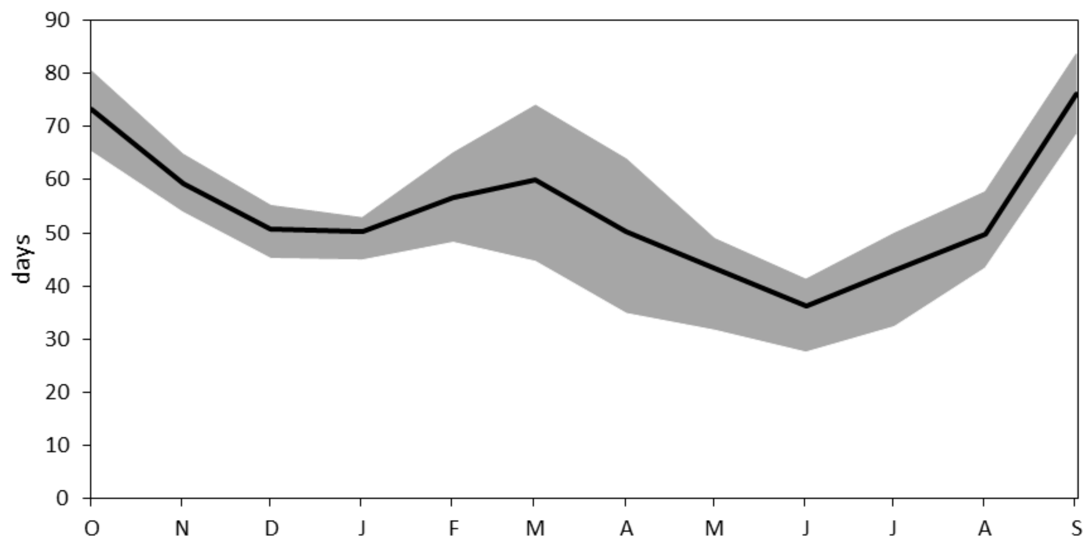


**Figure 2-7. Average monthly residence time of Lake Roosevelt presented in terms of the ratio between storage volume and flow rate for the 2000-2015 water years. Gray bounds represent the 20th- and 80th-percentile values.**

## 2.2.4 Conditions in 2015

The National Oceanic and Atmospheric Administration National Marine Fisheries Service (NOAA Fisheries) documents in their Adult Sockeye Salmon Report that migration conditions during June and July of 2015 were detrimental to Sockeye Salmon as Sockeye Salmon sustained heavy losses in the Columbia and Snake Rivers and tributaries (NOAA Fisheries 2016). Endangered Species Act (ESA)-listed Snake River Sockeye Salmon and Lake Wenatchee and Okanogan River Sockeye Salmon (Columbia River Sockeye) both exhibited poorer migration survival than recent history. Although adult survival from Bonneville to McNary Dam was higher for Upper Columbia River Sockeye than Snake River Sockeye Salmon during 2015, survival to the spawning grounds was poorer for both groups. Snake River Sockeye Salmon were especially affected in the mainstem migration corridor, with losses exceeding 95 percent between Bonneville and Lower Granite dams (NOAA 2016).[3] The cause of high losses has been linked to river conditions, including high river temperatures during migration. During the summer of 2015, low flow conditions (Figure 2-8 and Table 2-5) combined with higher than normal air temperatures (e.g., two Hydromet stations in Washington measured several warm events well above average; Figure 2-9) resulted in high stream temperatures in the Columbia and Snake Rivers, and their tributaries. The Columbia River volumetric runoff at Grand Coulee for the spring-summer period (April-

[3] Other species of salmon and steelhead typically migrate outside of this time period both as juvenile and adults and were not substantially impacted.

August) was well below the 30-year average at 42 MAF or 74 percent of average. The lower Columbia River and Snake River runoff volumes were even lower in comparison to the 30-year average at 67 percent (58 MAF) and 54 percent (11.5 MAF), respectively.

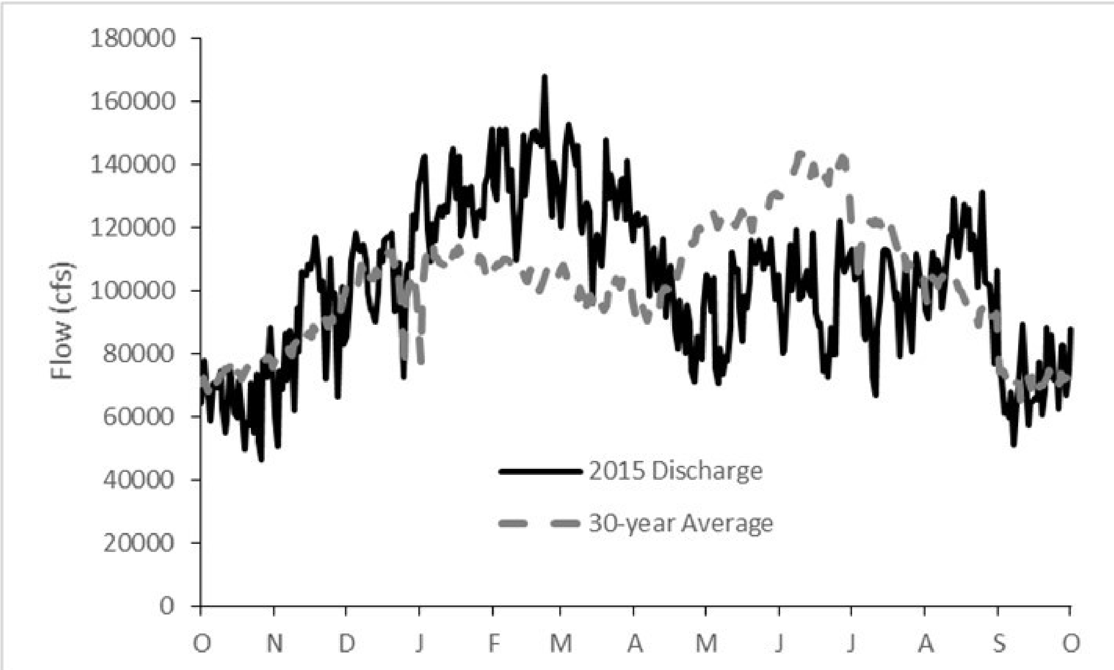


**Figure 2-8. Grand Coulee Dam outflows for water year 2015 vs. 30-year average.**

**Table 2-5. Runoff volumes by month for the Columbia River at Grand Coulee Dam, Snake River at Lower Granite Dam, and the Columbia River at The Dalles Dam (NWRFC 2016).**

| Water Year 2015 | October | November | December | January | February | March | April | May | June | July | August | September | April-August |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Columbia River at Grand Coulee Dam (KAF) | 3191 | 3878 | 3578 | 3102 | 5770 | 7123 | 6923 | 12351 | 12550 | 6146 | 4135 | 4024 | 42105 |
| Percent of average | 115 | 134 | 146 | 126 | 237 | 193 | 97 | 80 | 72 | 56 | 72 | 120 | 74 |
| Snake River at Lower Granite Dam (KAF) | 1256 | 1501 | 1958 | 2087 | 3188 | 3013 | 2919 | 4220 | 2350 | 1105 | 872 | 931 | 11466 |
| Percent of average | 88 | 93 | 111 | 106 | 141 | 90 | 64 | 61 | 39 | 48 | 70 | 78 | 54 |
| Columbia River at The Dalles Dam (KAF) | 4963 | 6363 | 7150 | 7185 | 11348 | 11959 | 11504 | 18333 | 15807 | 7552 | 5211 | 5245 | 58407 |
| Percent of average | 98 | 113 | 128 | 120 | 178 | 131 | 83 | 72 | 60 | 52 | 68 | 101 | 67 |

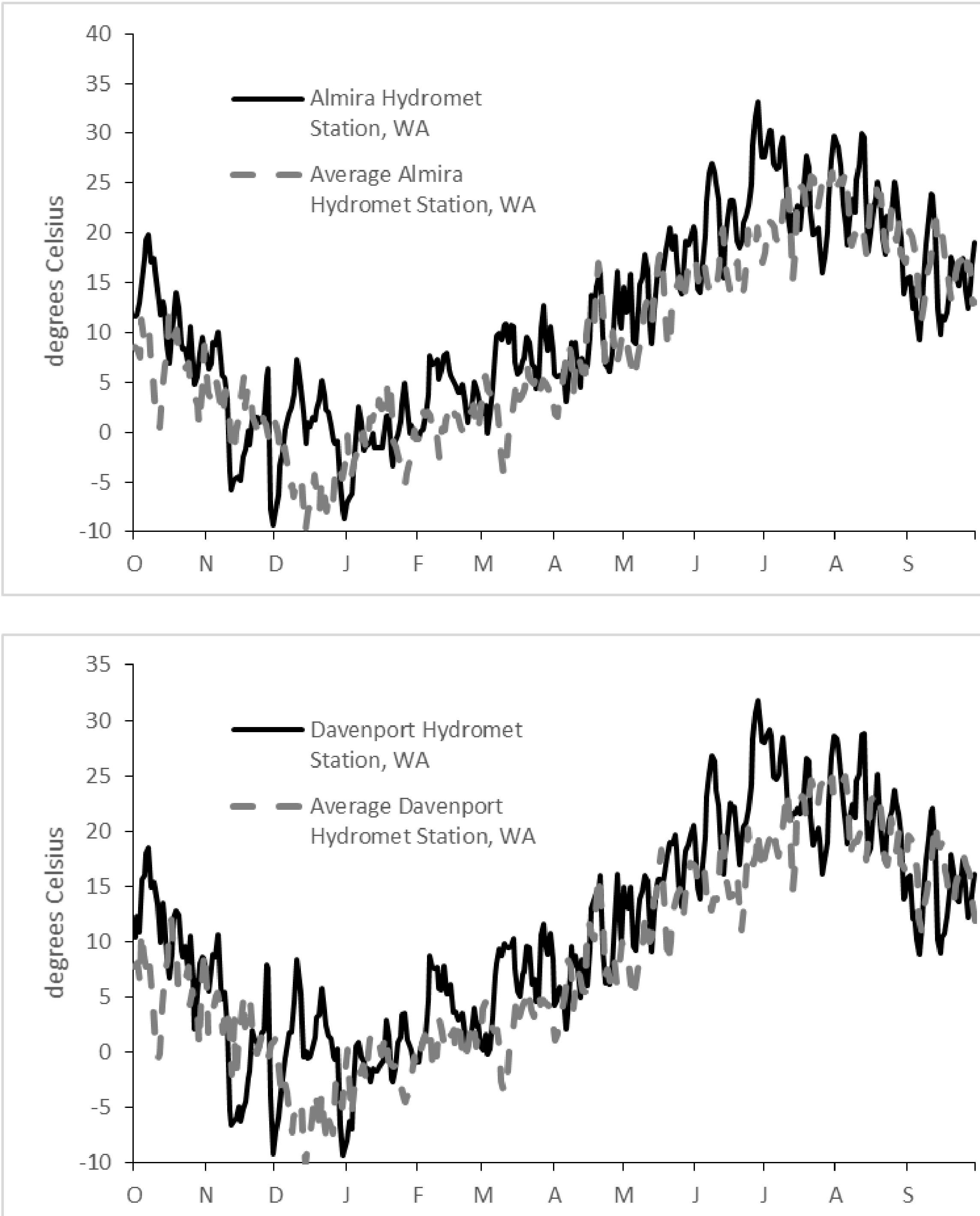


**Figure 2-9. Air temperatures at select Hydromet stations (Almira – top, Davenport – bottom) in Washington to characterize weather conditions during the 2015 water year (solid black line) compared to average conditions (dashed grey line).**

In 2015, Grand Coulee outflows during June and early July were 1 to 2ºC cooler than Columbia River temperatures upstream at the International Boundary (Figure 2-10). This is a pattern that occurs each year where Grand Coulee Dam releases water that is cooler than inflow during spring and summer and warmer during fall and winter (Section 2.2.1).

Inflow temperatures to Lake Roosevelt, as measured at the International Boundary, and outflow temperatures from Lake Roosevelt were slightly higher than normal (Figure 2-10). During June and July, the period when most adult sockeye migrate in the Columbia and Snake rivers, river temperatures downstream of Grand Coulee Dam were 13 to 19ºC in 2015, on average the temperatures during this period are 11 to 17ºC. The stratification in Lake Roosevelt followed a similar pattern as most years (Figure 2-11), with little stratification between the power plant intake elevations (see Table 2-4).

During the summer of 2015 the water temperatures increased by about 3˚C such that the daily average temperatures downstream of Priest Rapids Dam (near Pasco, WA) were 16 to 21ºC (average daily temperatures are typically between 14 to 20ºC for this period; see Figure 2-12).

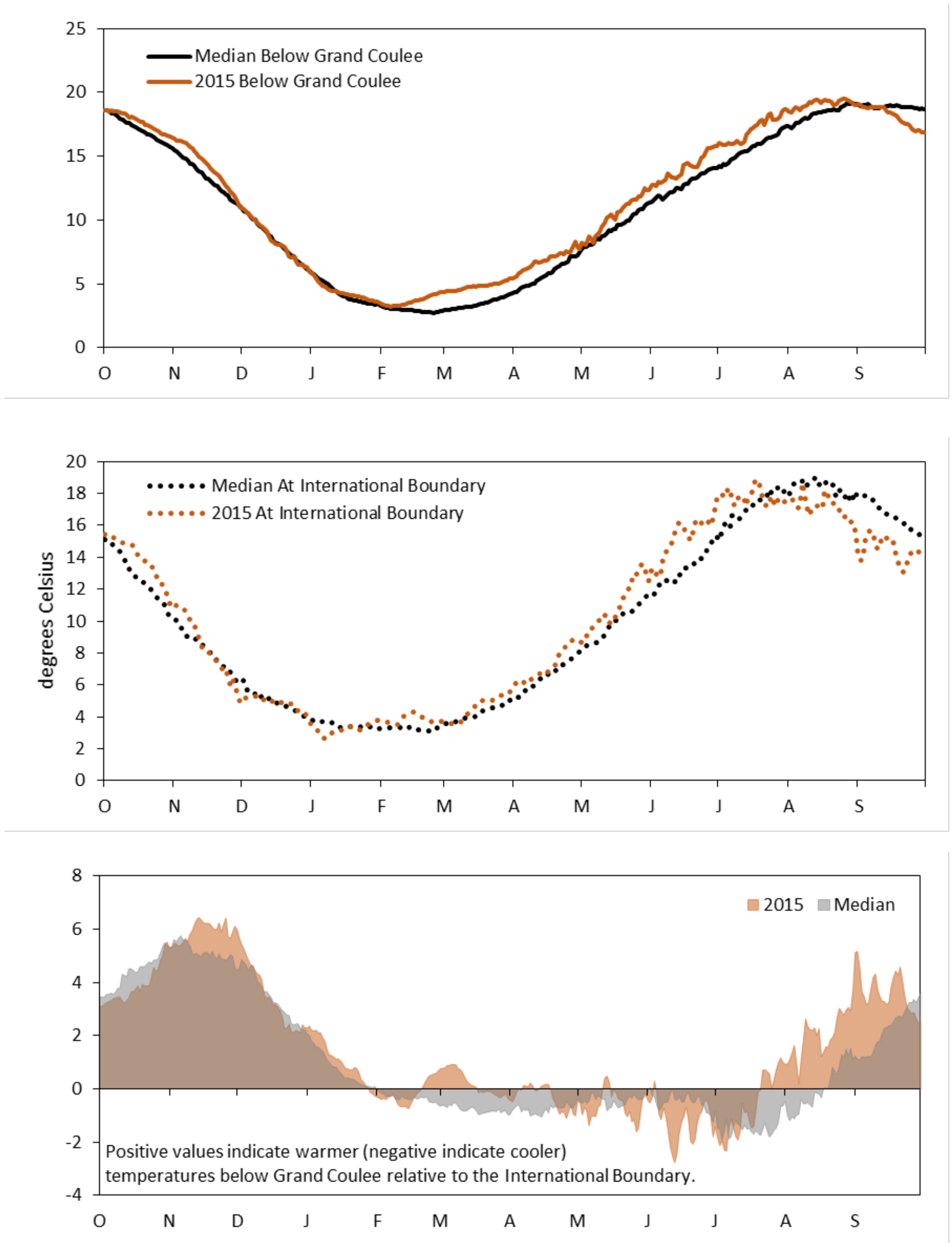


**Figure 2-10. Comparison of 2015 temperatures to 2000-2015 median temperatures on the Columbia River below Grand Coulee Dam near Barry, WA (top), at the International Boundary (middle), and in terms of temperature difference between these two locations (bottom).**

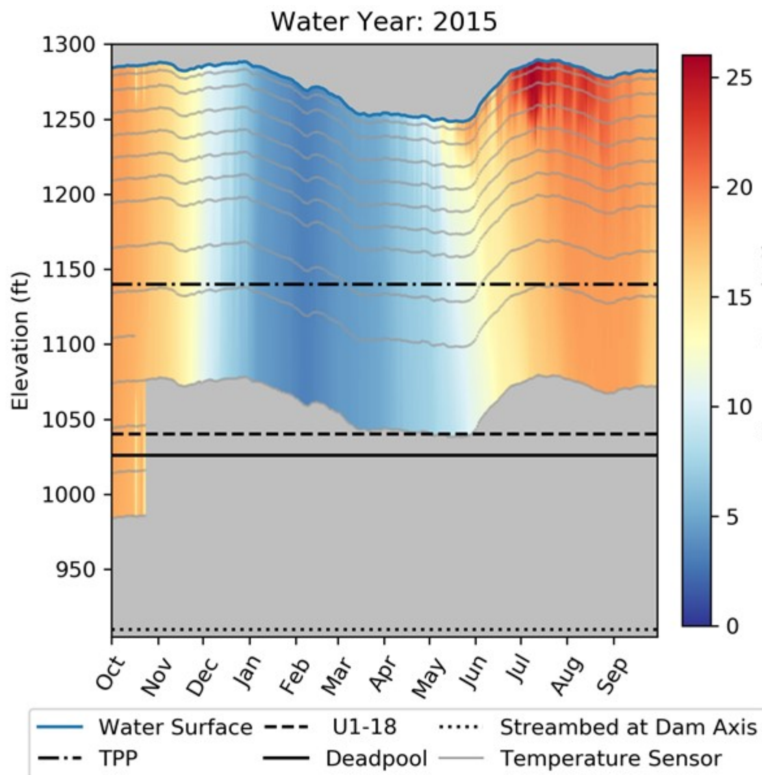


**Figure 2-11. Lake Roosevelt temperature profile for water year 2015. Grey background is missing data or above the water surface elevation. TPP is the Third Power Plant, U1-18 are the units of the Left and Right Power Plants.**

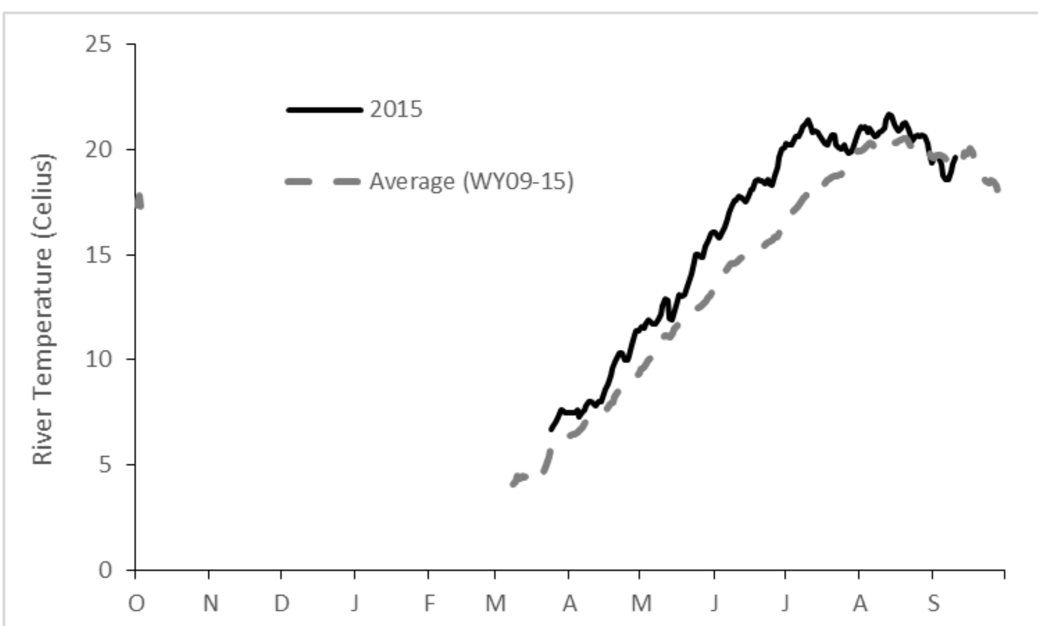


**Figure 2-12. Columbia River temperatures downstream of Priest Rapids Dam, near Pasco, WA. (Source: USGS 12514400 COLUMBIA RIVER BELOW HWY 395 BRIDGE AT PASCO, WA.)**

Daily Snake River temperatures as measured at Lower Granite Dam during the June-July period varied between 16 and 21ºC (typically average daily temperatures are between 12 and 19ºC for this period; Figure 2-13), similar to the temperatures below Priest Rapids in the Columbia River. Downstream of the confluence with the Snake the Columbia River continued to warm such that temperatures at The Dalles Dam varied between 17 and 24ºC (typically average daily temperatures are between 14 to 21ºC for this period; Figure 2-14).

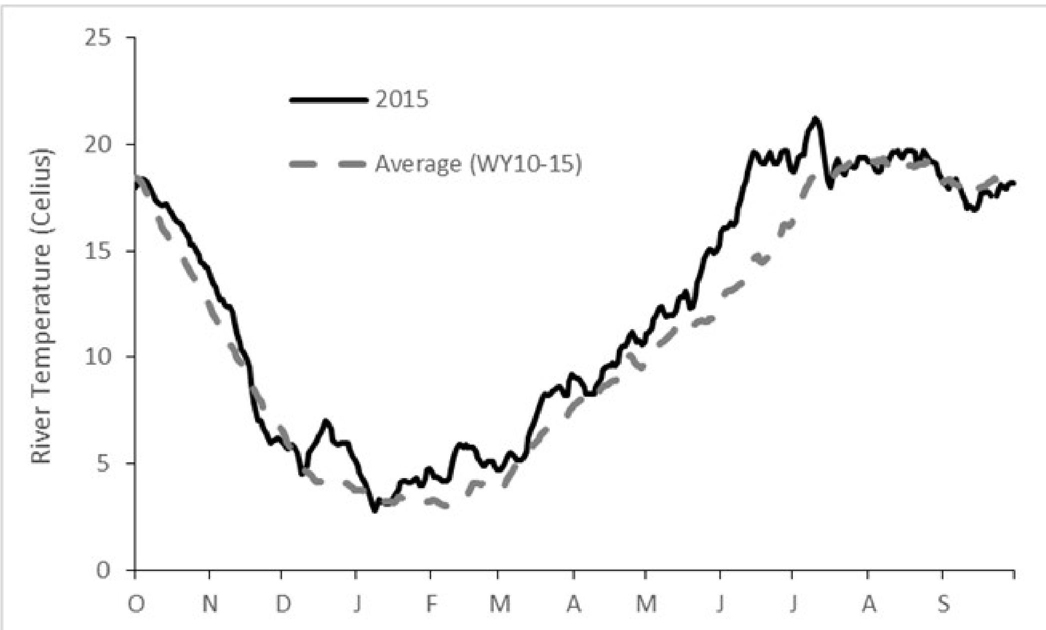


**Figure 2-13. Snake River temperatures downstream of Lower Granite Dam. (Source: USGS 13343595 SNAKE RIVER (RIGHT BANK) BL LOWER GRANITE DAM, WA.)**

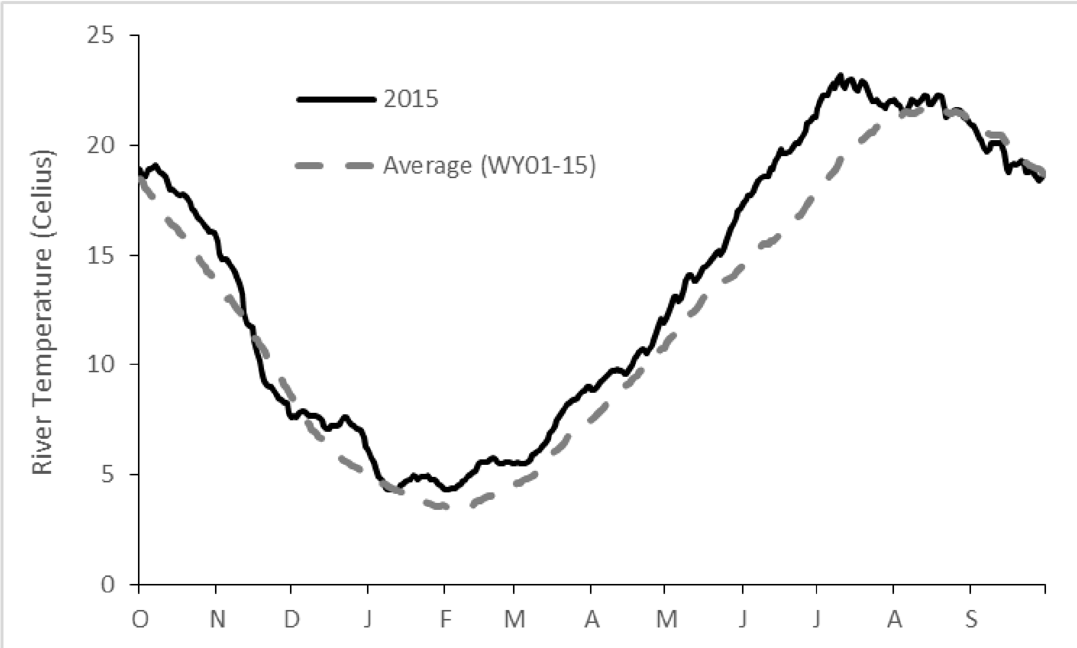


**Figure 2-14. Columbia River temperatures downstream of The Dalles Dam. (Source: USGS 14105700 COLUMBIA RIVER AT THE DALLES, OR.)**

It was not just the Columbia and Snake rivers that exhibited high temperatures in 2015. Tributaries of the Columbia and Snake rivers also exhibited temperatures well above normal in 2015. For example, the Salmon River, an unregulated tributary to the Snake River that provides migration and spawning habitat for the Snake River Sockeye, had temperatures in June and July that averaged 20ºC for the month, with a maximum daily average of 24.5ºC (Figure 2-15).

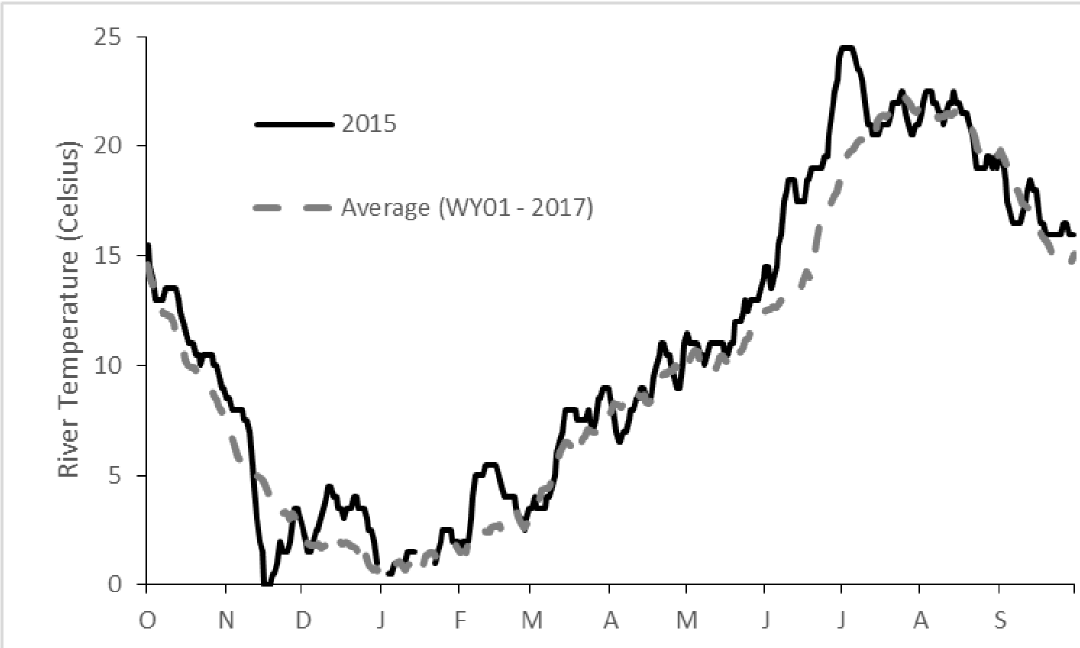


**Figure 2-15. Salmon River temperatures at Whitebird, Idaho. (Source: USGS 13317000 SALMON RIVER AT WHITE BIRD, ID.)**

In summary, the combination of high air temperatures and low flows resulted in above normal river temperatures in the Snake and Columbia rivers. As NOAA Fisheries (2016) documented, the temperatures in tributaries and upstream of storage projects were also well above normal. Inflow and outflow temperature at Grand Coulee were higher than normal during the June-July period but outflow temperatures were cooler than inflow temperatures. Grand Coulee operations during the sockeye migration in 2015 released the coolest water possible, but similar to conditions in the Snake River, the Columbia River warms as it moves downstream in the Middle-Columbia reach. The Columbia River temperatures increased several degrees between Grand Coulee Dam (RM 597) and McNary (RM 292) over roughly 300 miles.

## 2.3 Grand Coulee Current Operations and Constraints

Although cold water is not available in Lake Roosevelt, it is important to recognize that Grand Coulee Dam has many operating purposes, and it is these purposes, including the configuration of the dam, that limit the ability to release theoretical cool water from the reservoir. The operations of Grand Coulee Dam respond to a variety of factors including water supply conditions, power demand, and flow needs for fish. Under the current 2008/2010/2014 Biological Opinion (BiOp) operating plan, the combination of operational purpose and variable conditions result in pool elevation (Figure 2-16) and flow changes hourly, daily, and seasonally. The operations of Grand Coulee are highly constrained by these operating purposes, and leave little flexibility to modify for other operations.

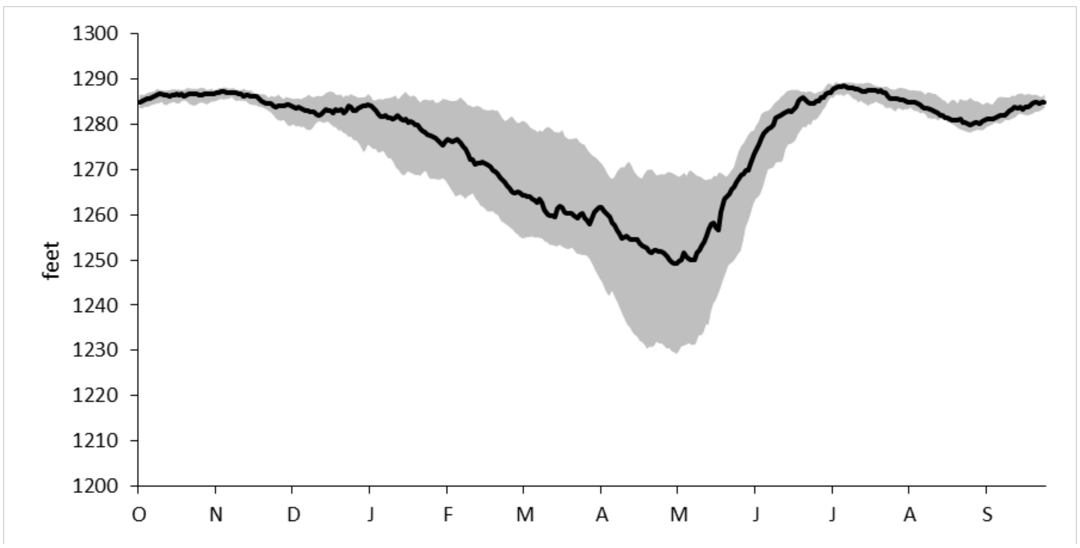


**Figure 2-16. Lake Roosevelt surface elevations, showing the median (dark line), 20 percent, and 80 percent exceedance (gray shade) for water years 1996 through 2016 under current operation regime.**

As previously discussed, Grand Coulee Dam has three power plants: Left Power Plant, Right Power Plant, and Third Power Plant (TPP). Generally, the Left and Right Power Plants operate at full capacity (considering scheduled maintenance outages, generating reserves, and power demand), and the TPP picks up generation during the daily peak-load periods. The Left and Right Power Plants run continuously (providing baseload) and are used to stabilize voltage during the night. They are also used to fine-tune power generation during the daytime peak-load periods. The TPP, which is substantially larger and more efficient than Left and Right Power Plants, is brought online in the morning to meet daytime power load. These load-following or peaking operations are illustrated in Figure 2-17.

There is relatively little flexibility to modify operations between power plants. The temperature differences between the Third, Left, and Right Power Plants are minimal, and the current operation releases the coolest water possible while maintaining power production.

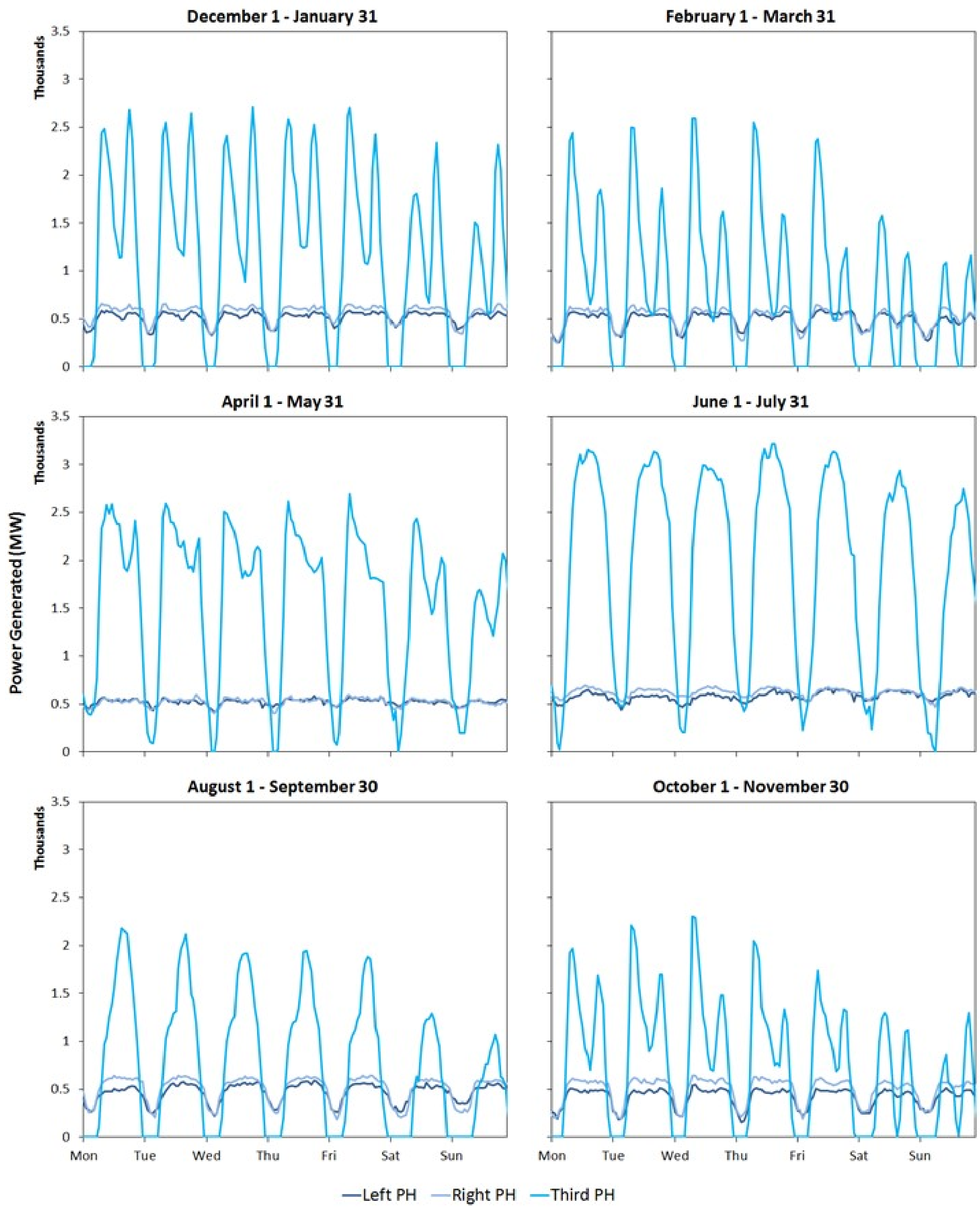


**Figure 2-17. Hourly power plants operations representing a typical year. The Left and Right Power Plants are used for base-loads, and the Third is used for peaking operations.**

Power demands, configuration of the plant, TDG standards, and maintenance outages constrain the operational flexibility of Grand Coulee Dam. Key power plant and outlet operational limitations include:

- **Power Demand and Voltage Stability –** Power generation at Grand Coulee is directed by the balancing authority to meet the regional power demand. Exclusive use of the Left and Right Power Plants would not provide sufficient power to meet demand. Exclusive use of the large and highly-efficient units in the Third Power Plant would make the 230-kV system more vulnerable to power system instability or voltage collapse[4] at the project which would be a major concern for the bulk electrical system of the Northwest.
- **Irrigation Demand –** Power to pump water from Lake Roosevelt to Banks Lake for irrigation of the CBP through the JWKII P/G is generated by units 1, 2, and 3 of the Left Power Plant. These units cannot be shut down during the irrigation season.
- **Peaking Operations –** Daily operations during the spring can vary significantly with daily outflows ranging from 0 cfs to more than 150,000 cfs within a 24-hour period. Exclusive operation of the Third Power Plant or of the Left and Right Power Plants do not allow for enough flexibility to meet these peak demands.
- **TDG Production by Non-Power Plant Outlets** - While the upper outlets (elevation 1,150 feet) and middle outlets (1,050 feet) provide additional flexibility with respect to the ability to pass water regardless of power limitations, these outlets generate high levels of TDG so their use is not considered a reasonable alternative for increasing daily operational flexibility.

The following description of seasonal operations considers the current purpose, constraints, and configuration of Grand Coulee Dam.

### 2.3.1 Fall Operations

During the fall, Reclamation’s operating priorities are power generation and supplemental flows for anadromous fish. By late September, Reclamation attempts to refill Lake Roosevelt to a minimum elevation of 1,283 feet to support resident fish in the reservoir. Beginning in October, Reclamation operates Grand Coulee Dam primarily to

[4] The 230 kV-system is the high-voltage transmission from the Left and Right Power Plants. Voltage collapse is a system instability involving many power system components, typically associated with power demand of load not being met due to shortage in power production and transmission.

support tail water[5] elevations for fish as necessary (spawning and protection flows in the Hanford Reach below Priest Rapids Dam for fall Chinook salmon at Vernita Bar) and to meet power needs (Grand Coulee's portion of the Firm Energy Load Carrying Capacity [FELCC]). In November, Grand Coulee Dam operates to support spawning and incubation elevations for lower Columbia River chum salmon below Bonneville Dam[6], as necessary. Reclamation limits any drafts for power to an elevation of 1,283 feet in October; 1,275 feet by the end of November; and 1,270 feet by the end of December. These elevation limits provide protection for resident fish, chum spawning/incubation below Bonneville, and BiOp refill (to augment flows during the spring and summer period for migrating salmon).

### 2.3.2 Winter Operations

During the winter season, Reclamation's operating priorities are FRM, power generation, and minimum flows for fish. Reclamation generally drafts Lake Roosevelt below the required FRM elevations to generate power and to provide flows for spawning or incubating chum salmon below Bonneville Dam. Such drafts are part of a strategy referred to as "winter power flexibility" and are used to help meet winter power demands in the northwest. Variable Draft Limits allow Lake Roosevelt to provide "winter power flexibility" while providing an 85 percent probability of achieving the April 10 pool elevation objective.[7] The April 10 pool elevation is intended to shape spring flows to benefit juvenile anadromous[8] fish migration.

Drum gate maintenance is scheduled to occur annually during March, April, and May. The drum gates are a critical dam safety feature and must be maintained. The reservoir must be at or below elevation 1,255 feet for 8 weeks to complete drum gate maintenance. At a minimum, drum gate maintenance must be completed at least once in a 3-year period, twice in a 5-year period, and three times in a 7-year period. The in-season criteria for accomplishing drum gate maintenance will be based on the FRM requirement for the April 30 maximum Grand Coulee elevation as determined by the February final April through August water supply forecast. The February forecast is used to allow sufficient time to draft the reservoir below 1,255 feet by March 15. If the February forecast sets the Grand Coulee April 30 FRM elevation at or below 1,255 feet, Grand Coulee will be drafted to perform drum gate maintenance. When the February forecast sets the April 30 FRM requirement above 1,265 feet, drum gate maintenance will be "forced" only if

[5] Tail water is the water immediately below the dam.

[6] Operations to support chum spawning start in November, October and early November operations target storage levels to setup winter operations, including potentially supporting chum operations.

[7] The April 10 elevation is an RPA in the 2008/2010/2014 FCRPS NOAA Fisheries Biological Opinion and is based on the Upper Rule Curve (used to operate the reservoir for FRM purposes).

[8] Anadromous fish, such as Pacific salmon species, that migrate from salt water to spawn in fresh water.

needed to meet the requirements of the 1 in 3, 2 in 5, and 3 in 7 criteria.  If the April 30 FRM requirement is between 1,255 and 1,265 feet, then maintenance will only be done if the following year would be a “forced” drum gate maintenance year.

### 2.3.3 Spring Operations

During the spring season, Reclamation continues operations for the purposes of FRM and power operation and begins operations for spring flow augmentation and irrigation.

As spring flow increases, Reclamation captures some of this flow to refill the reservoir, while continuing operations to support flow augmentation for juvenile salmon and steelhead migrating downstream.  The flow augmentation releases in the spring are enhanced by Lake Roosevelt and can be drafted below the April 10 elevation to help provide protection flows for Hanford Reach fall Chinook salmon redds[9], as well as to support chum incubation coordinated with the Technical Management Team, an interagency technical group responsible for making recommendations on dam and reservoir operations.

Irrigation withdrawals do not begin until March remaining relatively light until April. Reclamation delivers over 3 MAF of water annually to irrigate over 758,000 acres within the CBP.  Water is supplied to the CBP through Banks Lake, which is located adjacent to Grand Coulee Dam and extends approximately 27 miles towards the southwest

During spring or early summer when required releases exceed power demand or unit availability, water must be spilled (bypassing the turbines) at some of the Columbia and Snake River power plants[10] (known as involuntary spill[11]).  Spill past the turbines generates TDG which can be detrimental to aquatic species.  Since Grand Coulee is part of an integrated system with other federal dams, they are coordinated together to minimize system TDG consistent with state water quality standards.  Below an elevation of 1,265.5 feet at Lake Roosevelt, water must be spilled through the regulating outlet works which consist of both upper and mid-level outlets.  These outlets generate a significant amount of TDG and therefore, used only when necessary.  Drum gates are preferred for spill because they do not generate as much TDG.  Involuntary spill operations generally only occur during FRM operations in the spring and early summer, typically April into July.  Spill that occurs in June and early July is typically over the drum gates and is warmer than the water going through the power plants, although this is usually during wet years when temperature is less of an issue in June and July.  By mid-

[9] A redd is the spawning nest made by fish, specifically salmon.

[10] Powerplant refers to the entire project, while power plant refers to an individual component, for example Third Power Plant.

[11] Involuntary spill is not by choice, but the project needs to release more water than can be put through the units.  Some projects (typically those that have fish passage) release spill voluntarily to supports fish migration downstream.

summer, spill is usually not necessary as there is lower outflow and sufficient power demand, and therefore, hydraulic capacity, to pass flow through the power plant.

### 2.3.4 Summer Operations

During the summer season, Reclamation's operating priorities are irrigation, flow augmentation[12] for fish, and power generation. The reservoir typically refills by early July.

Summer flow augmentation draft levels are determined by forecast. The draft begins after the reservoir reaches its fullest point, in early July, and concludes by the end of August. Reclamation will draft Lake Roosevelt to 1,280 or 1,278 feet by the end of August to supplement flow at McNary for fish. If the July final forecast (as defined in the Water Management Plan) for the April through August period at The Dalles is less than 92 MAF, the draft limit[13] is elevation 1,278 feet; otherwise, the draft limit is elevation 1,280 feet. The August 31 draft limit will be adjusted an additional amount, up to 1.0 feet in non-drought years and 1.8 feet in drought years (as defined by Washington Administrative Code 173-563-056) to implement the Lake Roosevelt Incremental Storage Release Program (LRISRP).[14] The draft of Lake Roosevelt for LRISRP is to supply water for M&I, streamflow enhancement, and irrigation in the Odessa area.

### 2.3.5 Summary of Dworshak Dam Operations and Water Temperature

A brief description of the USACE' Dworshak Dam is provided as a comparison and contrast to Grand Coulee Dam. Although both water storage projects, their hydrologic conditions, thermal regimes, and operations are very different. Dworshak Dam was selected for this comparison because it is the regional model for a water storage project that is operated to influence downstream temperatures for ESA-listed anadromous fish. Dworshak Dam is often cited as the example for how stakeholders would like to see Grand Coulee operate.

Dworshak Dam on the North Fork Clearwater River is 1.9 miles upstream of the mainstem Clearwater River. The concrete gravity dam is 717 feet tall (632 feet effective hydraulic height), with a crest length of 3,287 feet and a total storage capacity of 3,468,000 acre-feet of which 2 MAF are used for power generation and FRM (USACE 2016). Dworshak Dam's penstock intakes are equipped with adjustable gates for

[12] Flow augmentation is a term to describe increased flow released for fish.

[13] Draft limit refers to the pool elevation that meets an operational objective.

[14] Drought years are defined by Washington to be when the March 1 forecast for April through September runoff at The Dalles is less than 60 MAF.

selective withdrawal of water between full pool (1,600 feet) and minimum pool (1,445 feet) elevations (USACE 2016). The purpose of the selective withdrawal is to discharge water at a temperature suitable for fish production at the downstream Dworshak National Fish Hatchery while providing cold water releases during flow augmentation; these are often conflicting purposes. The project is operated in July through August for flow augmentation by releasing storage water to increase downstream flows for increasing water velocities in the lower Clearwater and Snake rivers and to moderate river temperatures, improving water quality. The amount of cold water available from Dworshak Dam for flow augmentation is approximately 1.2 MAF (BPA et al. 2016).

In contrast to the Columbia River at Grand Coulee Dam, the thermal conditions of the North Fork Clearwater River at Dworshak Dam are much cooler in the summer (see Table 2-3). This is due to the cooler inflows to the reservoir and because of the thermal stratification that occurs in Dworshak Reservoir. On average inflows into Dworshak Reservoir can fill the entire capacity (~3.5 MAF) once each year (average annual flow at Dworshak Dam is 3.9 MAF, or about 5,300 cfs). The monthly average residence times (i.e., storage volumes divided by flow rates) range from 87 days in August to 348 days in December. Figure 2-18 compares the residence time of Dworshak Reservoir to Lake Roosevelt. The inflowing temperatures and longer residence time are conducive to strong thermal stratification during the summer at Dworshak, as shown by Figure 2-19 and Figure 2-20). The water that is released from Dworshak can take advantage of the stratification, and release cooler water from the hypolimnion during mid- to late-summer months, resulting in cool releases well below equilibrium temperature (as seen by relatively cool water in the Clearwater River downstream of the confluence of the North Fork and Mainstem; Figure 2-21).

Temperature differences between the Snake River and Clearwater River at the confluence, near the upstream edge of Lower Granite Reservoir, is typically 10°C or more during July and August (Cook et al. 2006). The volume of water coming in from both the Clearwater and Snake rivers are similar in magnitude, and because of the temperature related density difference between the two rivers during summer flow augmentation periods the water does not mix immediately, so the Snake River, Lower Granite Reservoir as well as the other three reservoirs downstream stratify (Cook et al. 2006).

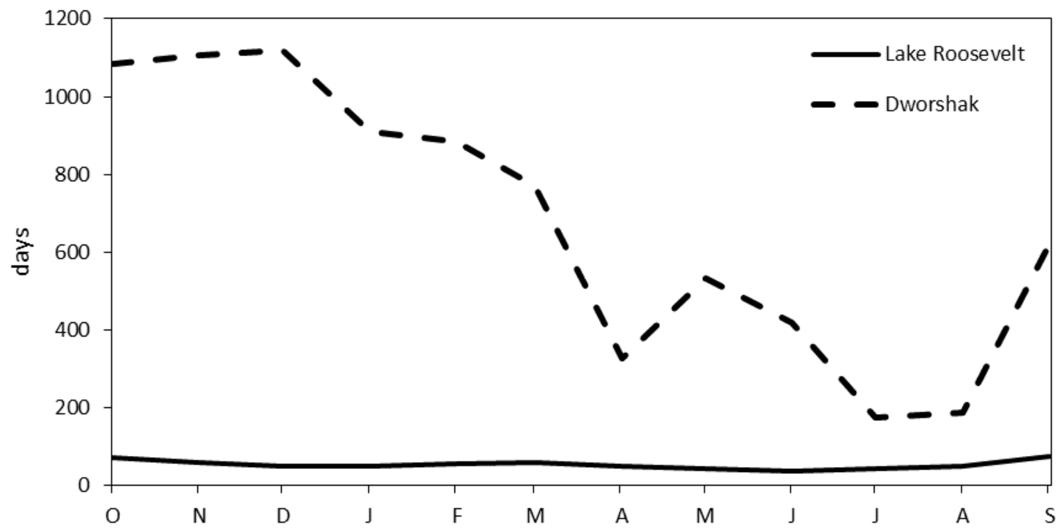


**Figure 2-18. Monthly average residence time of Lake Roosevelt and Dworshak Reservoir in terms of the ratio between storage volume and flow rate for the 2000-2015 (2003-2015 for Dworshak) water years.**

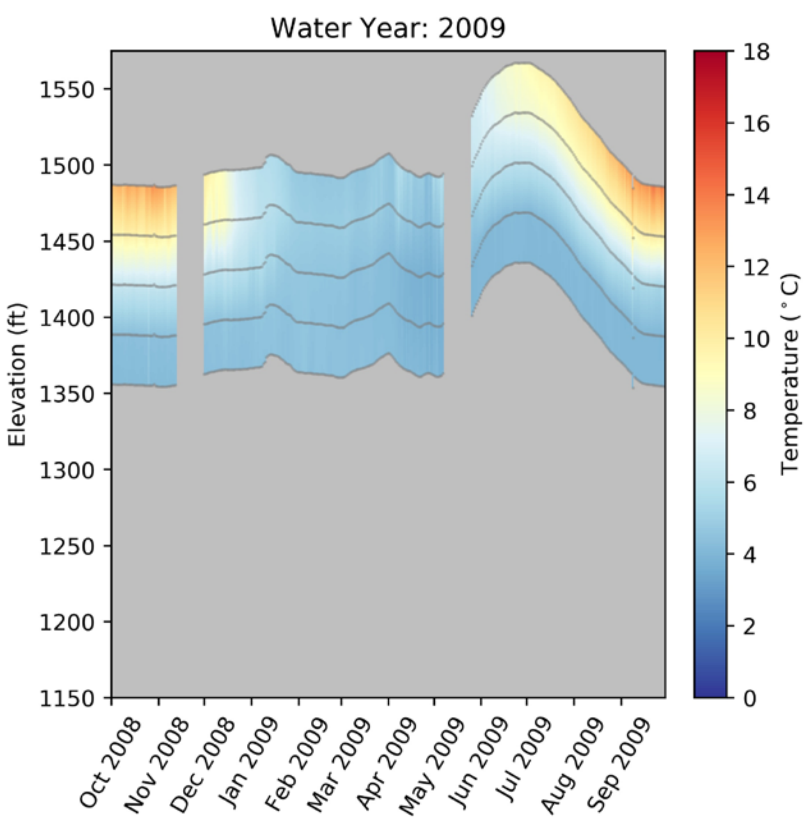


**Figure 2-19. Thermal stratification of Dworshak Reservoir for water year 2009, the temperature scale has been adjusted to allow visualization of the stratification. The color scale ranges from 0 to 18ºC.**

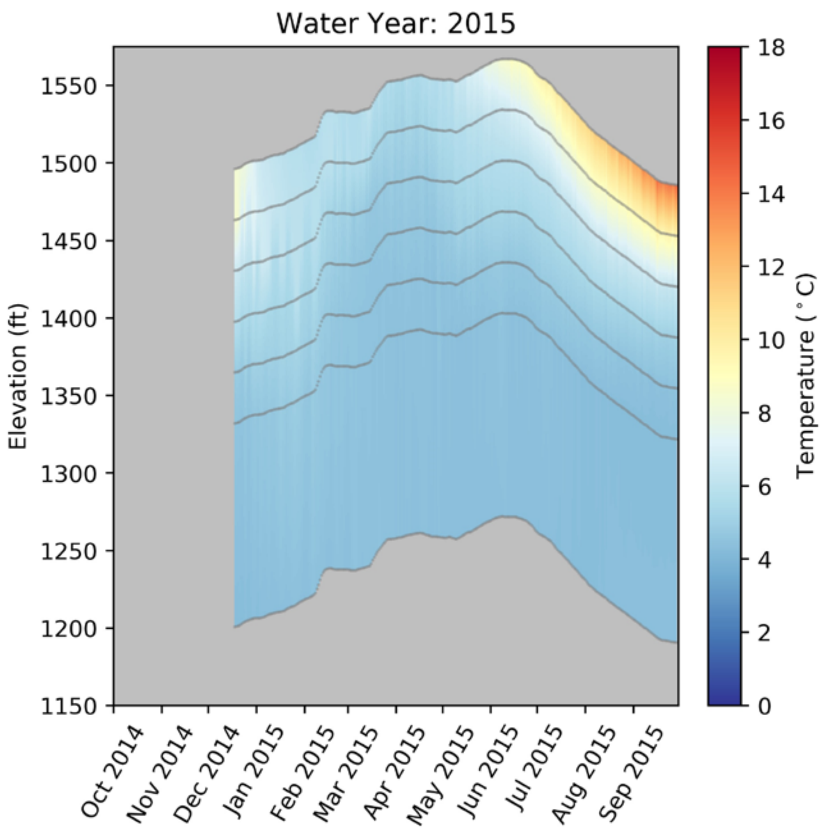


**Figure 2-20. Thermal stratification of Dworshak Reservoir for water year 2015, the temperature scale has been adjusted to allow visualization of the stratification. The color scale ranges from 0 to 18ºC.**

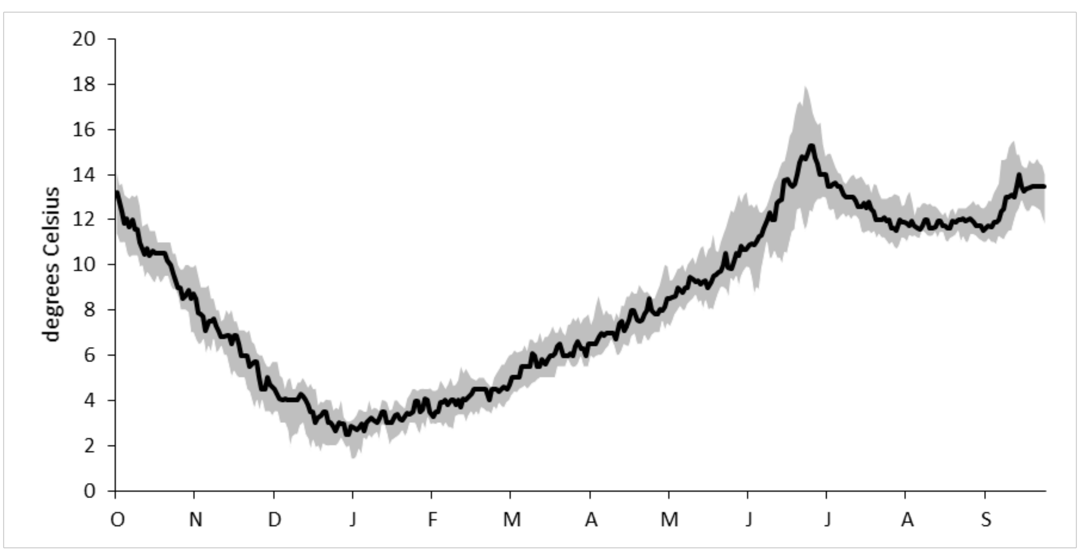


**Figure 2-21. Water temperatures measured in the Clearwater River downstream of the confluence of the North Fork and mainstem (USGS 13342500 CLEARWATER RIVER AT SPALDING ID), showing the median, 20 percent and 80 percent exceedance temperatures for water years 2006 through 2017 (using available data).**

In summary, Dworshak Dam has operational ability to release cool water because the water in the reservoir exhibits strong stratification, the dam has a selective withdrawal system that can access water at elevations in the reservoir with desired water temperatures, and is less operationally constrained and complex than Grand Coulee Dam.

The key differences between Grand Coulee Dam and Dworshak Dam include:

- Dworshak reservoir is much cooler (the Dworshak summer releases are well below 'equilibrium' temperature[15] of the lower Snake River) than Lake Roosevelt;
- Greater thermal stratification in Dworshak Reservoir than in Lake Roosevelt; Lake Roosevelt does have thermal stratification however, it is just shallow and weak;
- Longer water particle residence time in Dworshak Reservoir than in Lake Roosevelt; and
- Dworshak Dam has operational flexibility and structural configuration (the selective withdrawal structure) that allow for dedicated operations to take advantage of cooler reservoir temperatures. In contrast, Grand Coulee operations are highly constrained and complex (multiple power plants), and the operations currently release the coolest water possible in the summer.

# 3 CONCLUSION

Warm water events that affect anadromous fish species (e.g., the summer of 2015), highlight the need for fish and water managers to investigate potential actions that would reduce water temperatures and reduce risk to migrating fish. Some storage reservoirs can develop thermal stratification. A good example of this type of reservoir is Dworshak Reservoir on the Clearwater River in Idaho, the reservoir most often referenced for the perceived potential of Grand Coulee Dam to operate for temperature mitigation. Although Grand Coulee Dam is a large storage reservoir, the relatively large volume of flow through the reservoir, with respect to storage capacity, results in a reservoir that does not exhibit strong thermal stratification.

In summary, Grand Coulee Dam currently operates to release the coolest available water in the warm summer months. Little additional potential exists to mitigate for downstream temperatures due to a combination of lack of stratification, higher summer reservoir temperatures.

[15] Equilibrium temperature is defined as the point when two objects in contact, in this case the atmosphere and river, and the next exchange of energy is zero.

# 4 REFERENCES


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# 5 APPENDIX A: GRAND COULEE DAM AND FRANKLIN D. ROOSEVELT RESERVOIR THERMAL STRATIFICATION

Water temperature data is collected from a string of temperature loggers hung from a log boom approximately 2,000 feet upstream of Grand Coulee Dam. Temperature data is collected at the following elevations (in feet): 5’, 15’, 30’, 45’, 60’, 75’, 90’, 120’, 150’, 180’, 240’, 270’, and 300’. Sensor elevations are referenced from water surface (0’) and not distance from the lake bottom; therefore, 240’, 270’ and 300’ readings may not be available at lower forebay surface elevations. The water year plots in this appendix represent water temperature normalized to elevation, by correcting the sensor depth to the forebay elevation on the date the data is recorded. This data has been checked for quality but poor data could still exist, additionally the data should not be considered accurate beyond 0.5℃.

Figure 5-1 is an example year to demonstrate the components of the reservoir temperature plots. The vertical component of the plot is elevation, with the top blue line being the water surface elevation in the reservoir. The thermistors (temperature sensors) locations are shown by the grey lines. The temperatures (color map) represented between the grey lines are interpolated from available data, unless multiple sensors are missing then no interpolation is done and the space is left blank (grey background).

During later spring and summer, the reservoir stratifies, but most of this stratification is at or near the surface. Temperatures at the elevations of the power plant intake elevations are very similar.

The data associated with the following graphs is available here: https://www.usbr.gov/pn/hydromet/gcl-profiles/index.html.

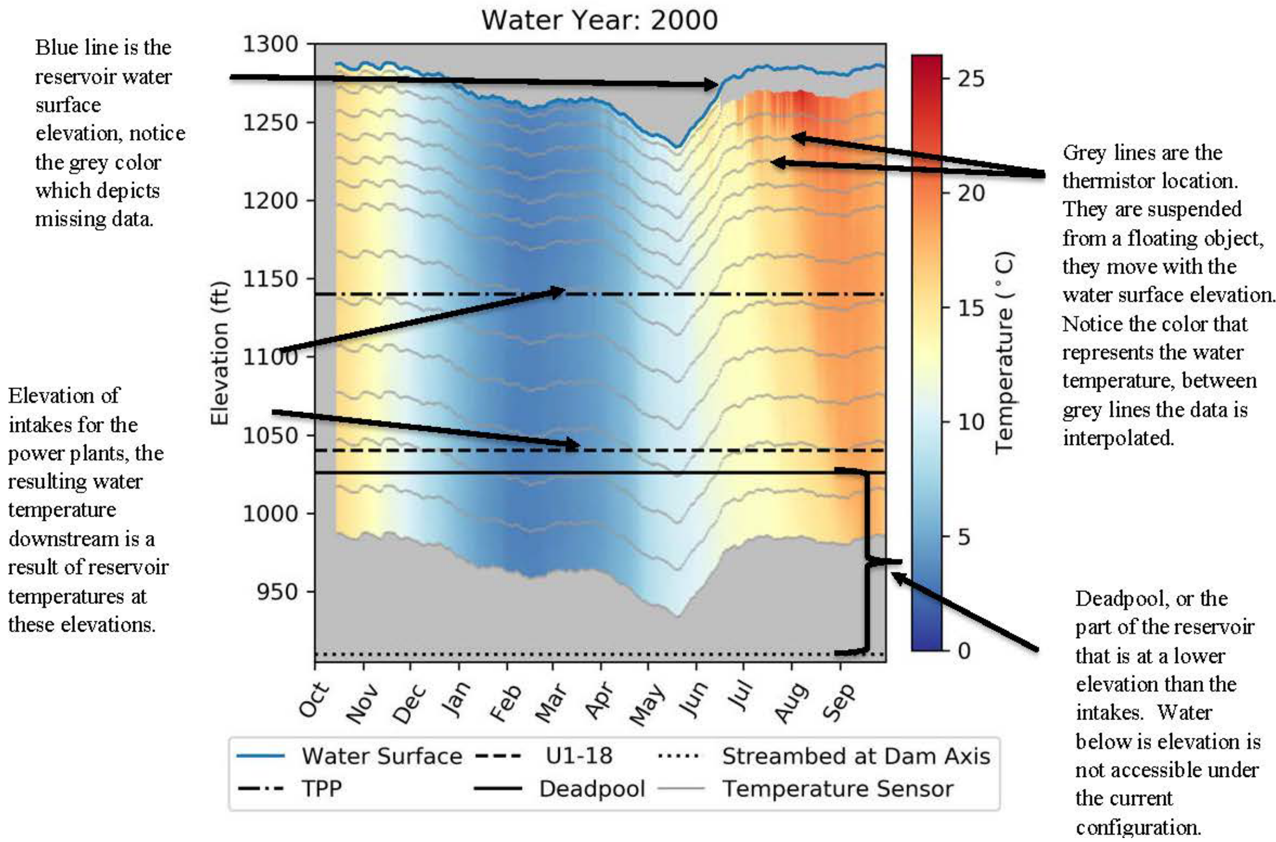


**Figure 5-1. Thermal stratification figures to demonstrate how to read figures in this appendix.**

The following figures (Figure 5-2 through Figure 5-18) display the pool temperature data for Lake Roosevelt for water years dating back from 2016 to 2000, the color scale represents 0 to 25°C.

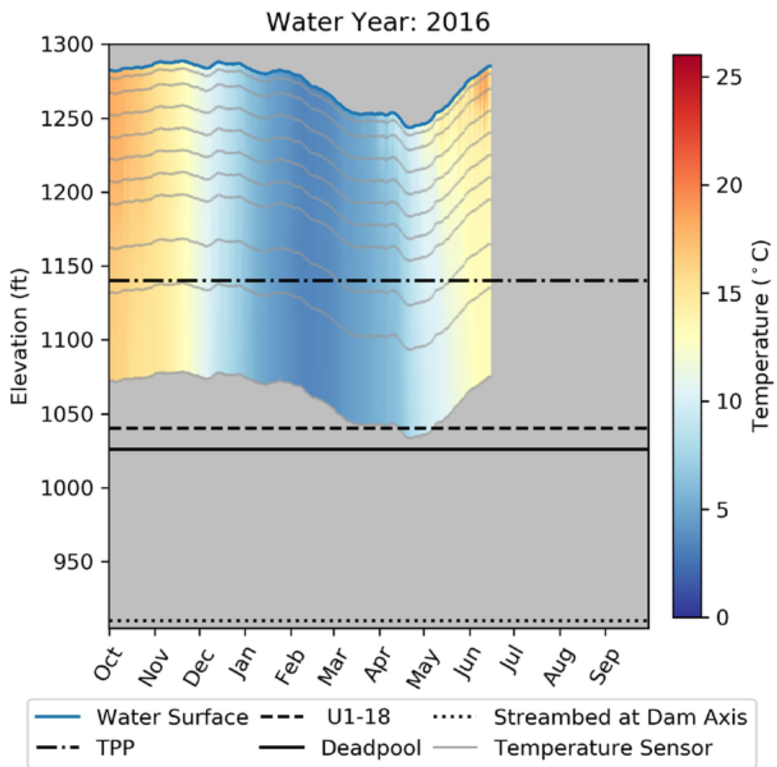


**Figure 5-2. Lake Roosevelt thermal stratification for water year 2016.**

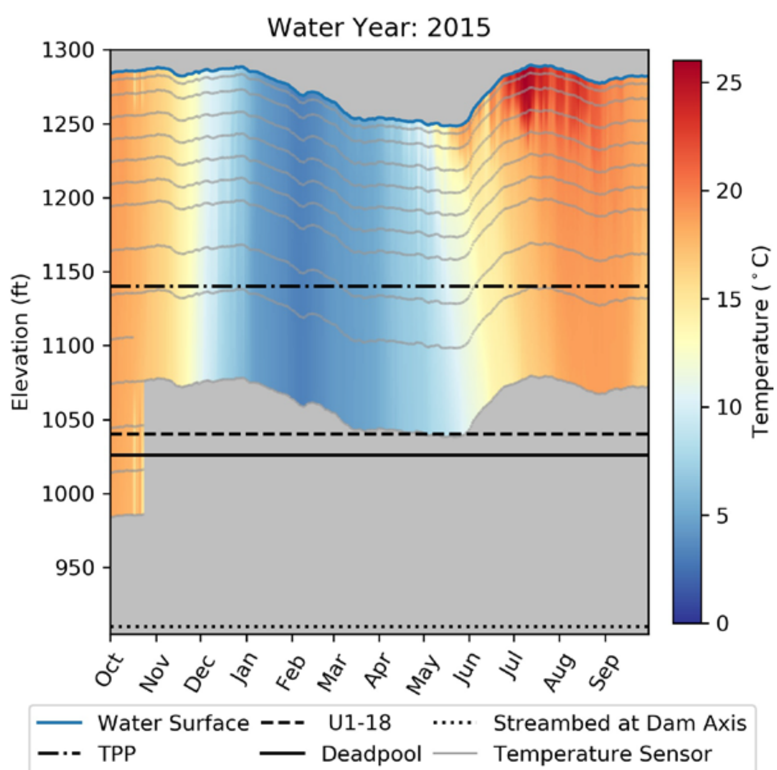


**Figure 5-3. Lake Roosevelt thermal stratification for water year 2015.**

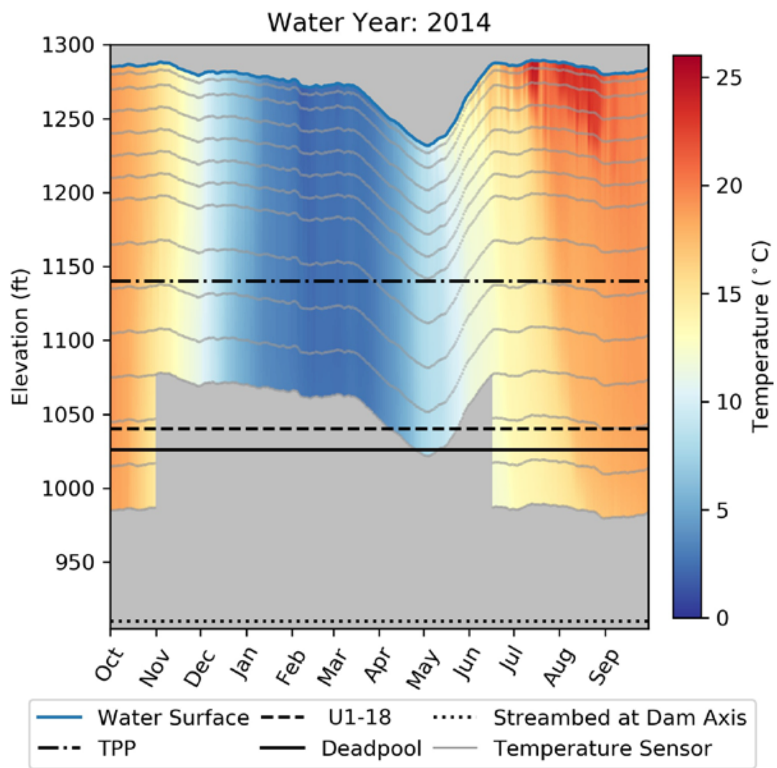


**Figure 5-4. Lake Roosevelt thermal stratification for water year 2014.**

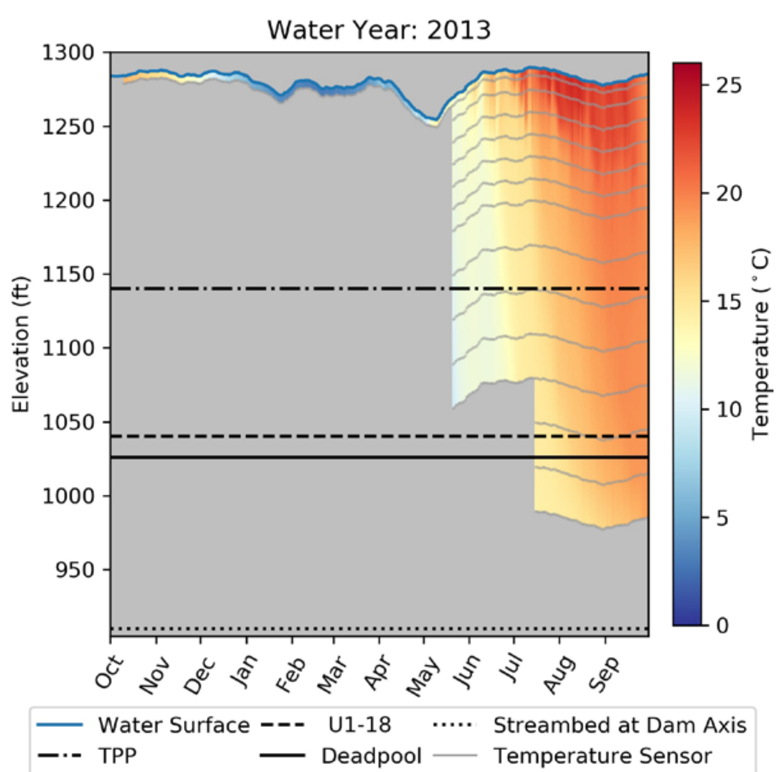


**Figure 5-5. Lake Roosevelt thermal stratification for water year 2013.**

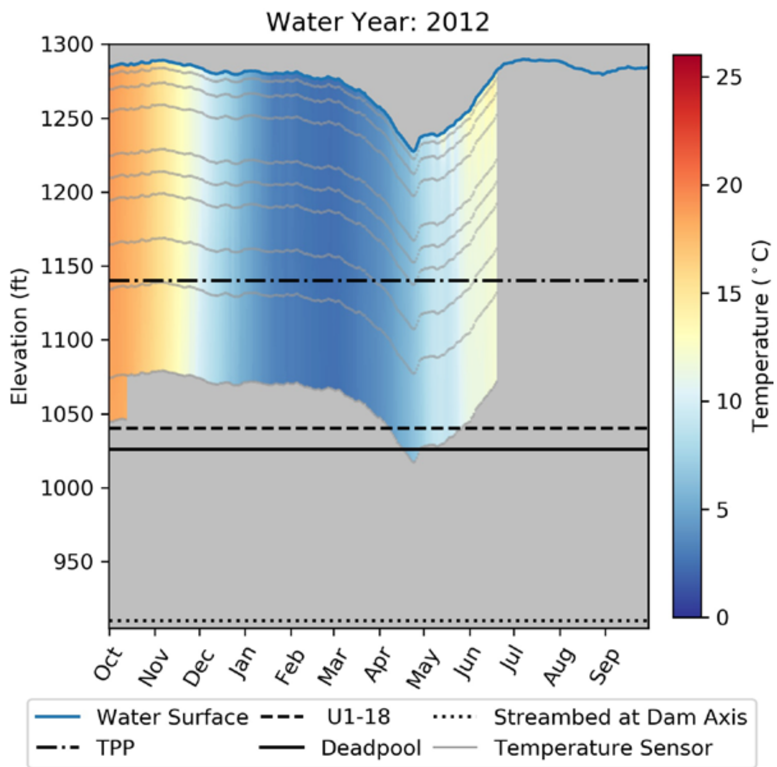


**Figure 5-6. Lake Roosevelt thermal stratification for water year 2012.**

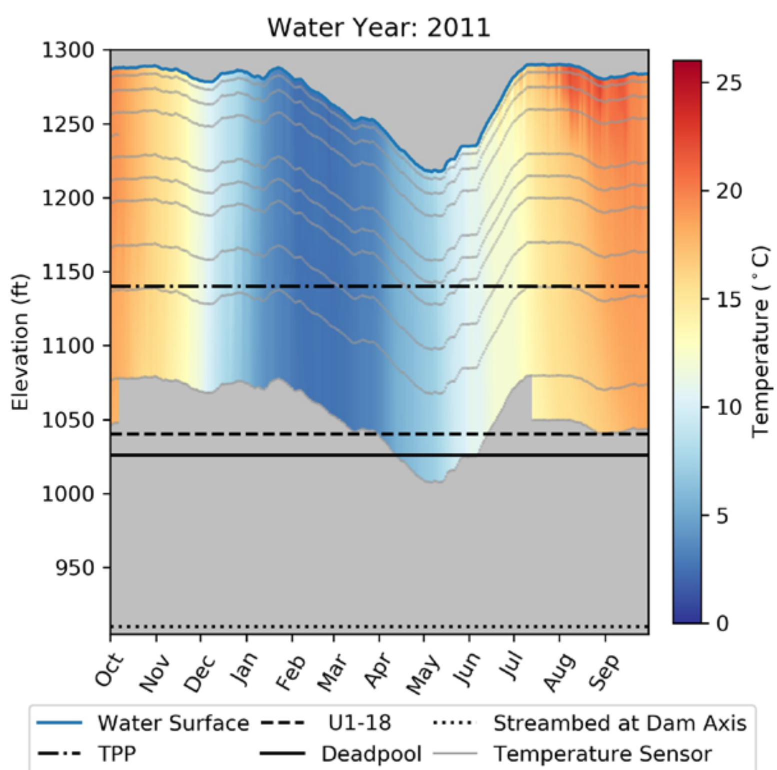


**Figure 5-7. Lake Roosevelt thermal stratification for water year 2011.**

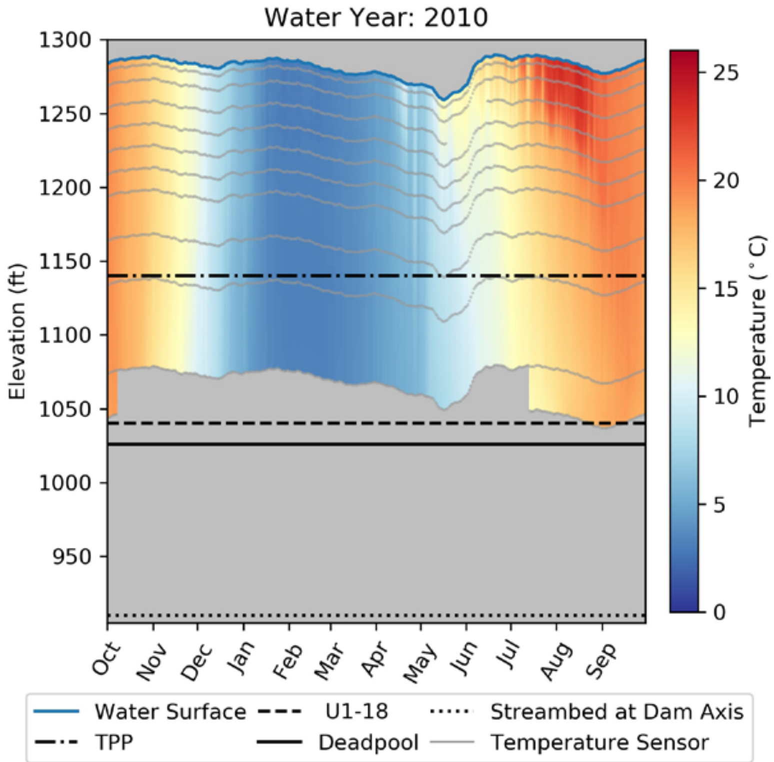


**Figure 5-8. Lake Roosevelt thermal stratification for water year 2010.**

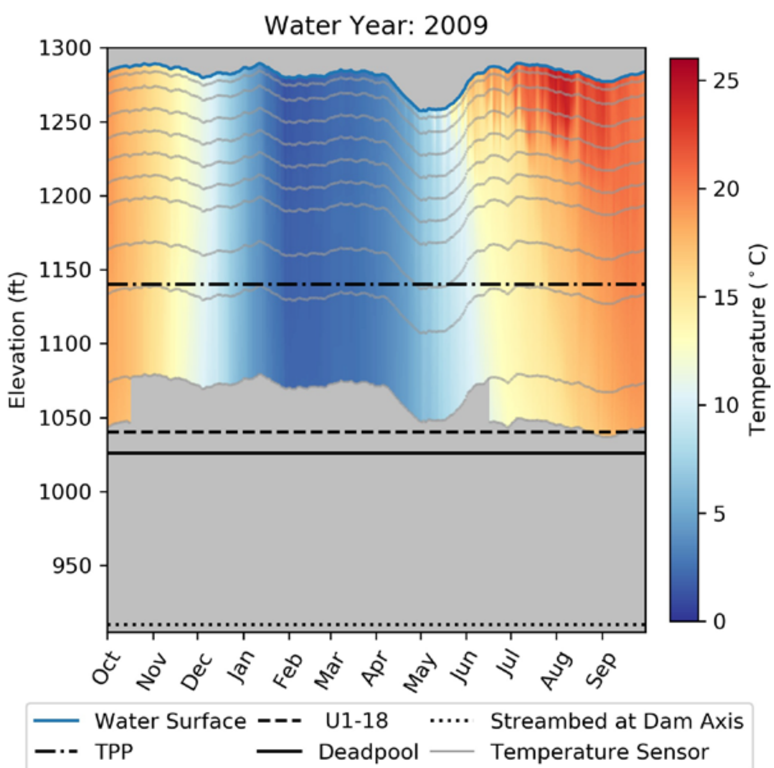


**Figure 5-9. Lake Roosevelt thermal stratification for water year 2009.**

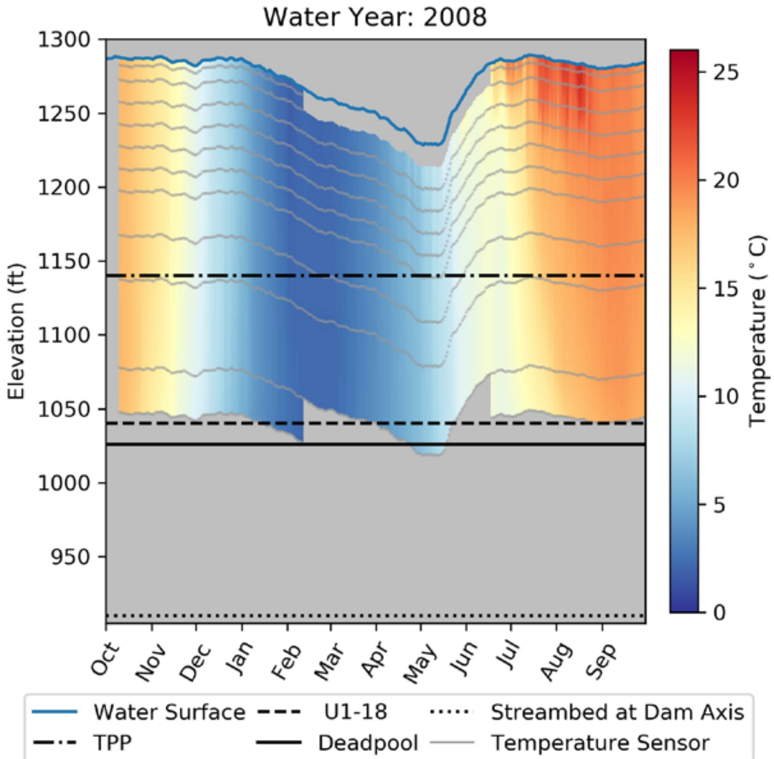


**Figure 5-10. Lake Roosevelt thermal stratification for water year 2006.**

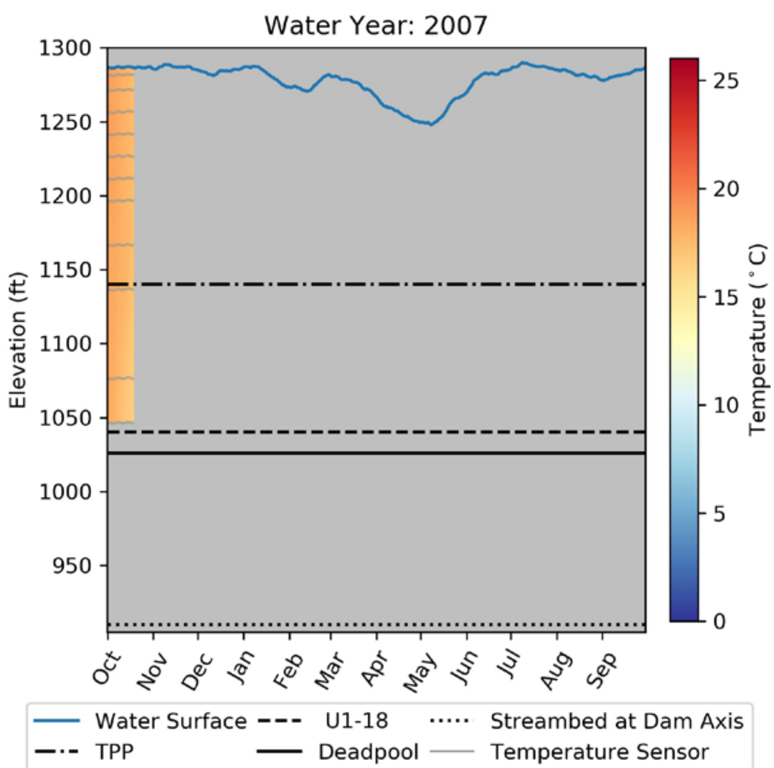


**Figure 5-11. Lake Roosevelt thermal stratification for water year 2007.**

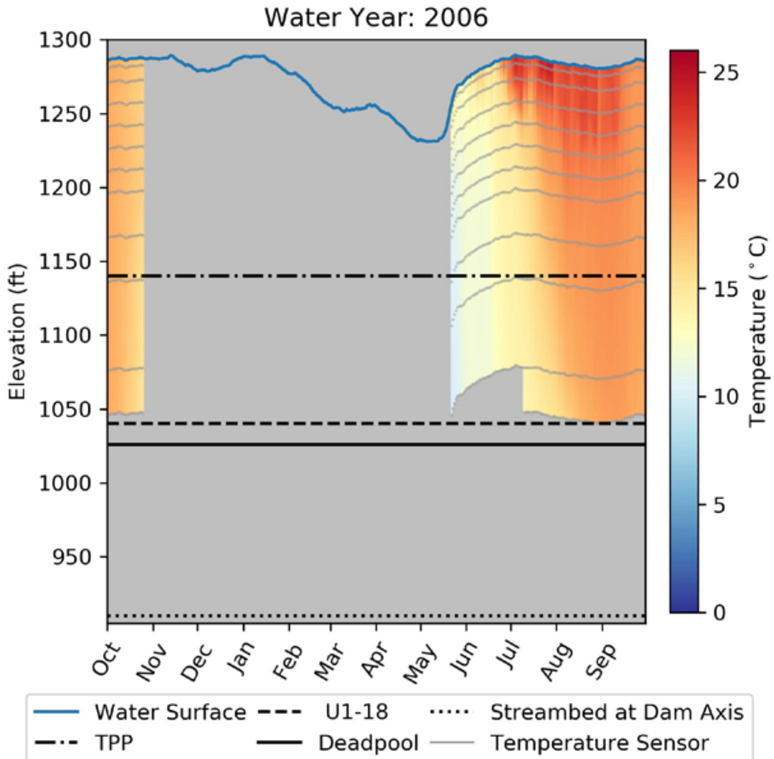


**Figure 5-12. Lake Roosevelt thermal stratification for water year 2006.**

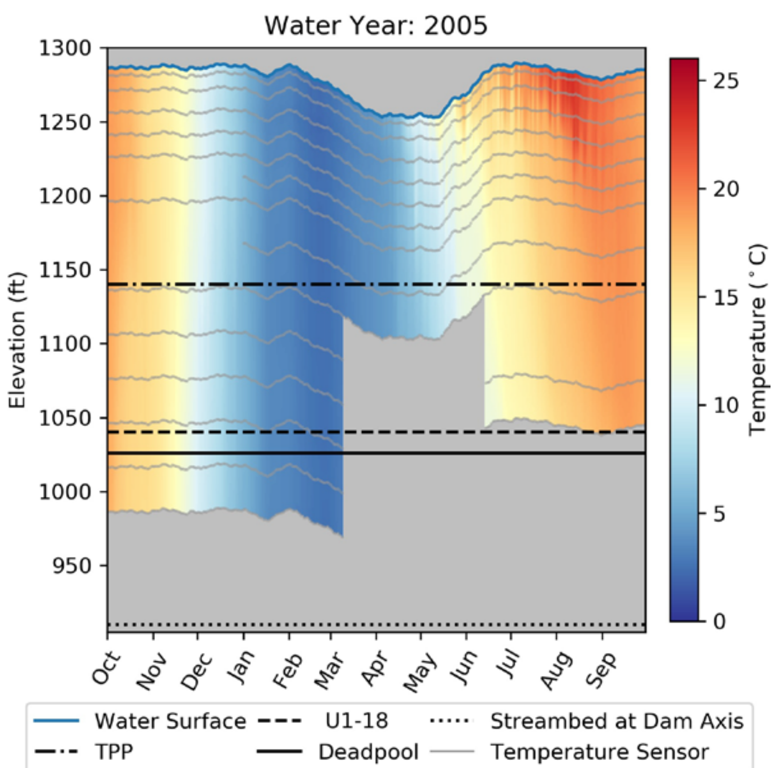


**Figure 5-13. Lake Roosevelt thermal stratification for water year 2005.**

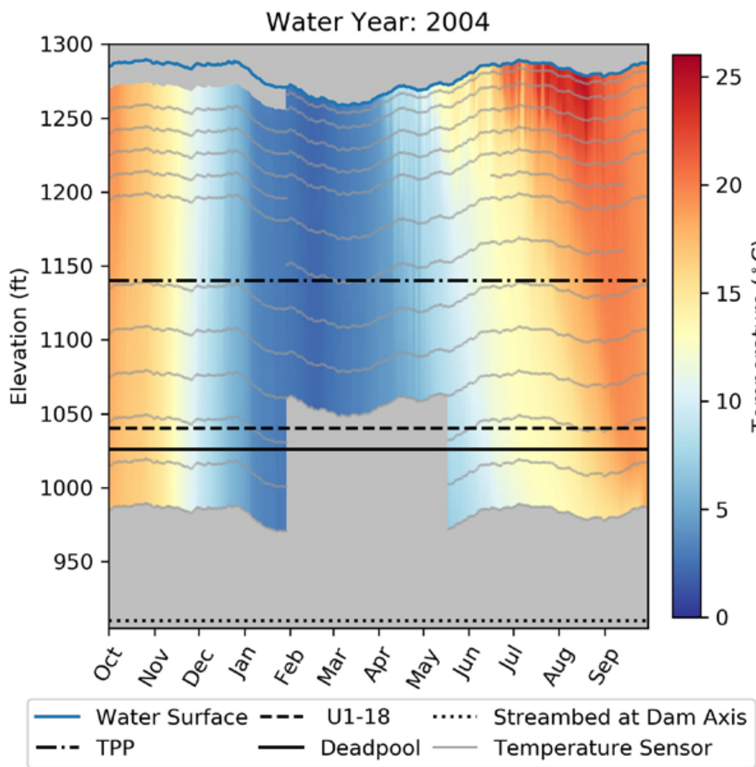


**Figure 5-14. Lake Roosevelt thermal stratification for water year 2004.**

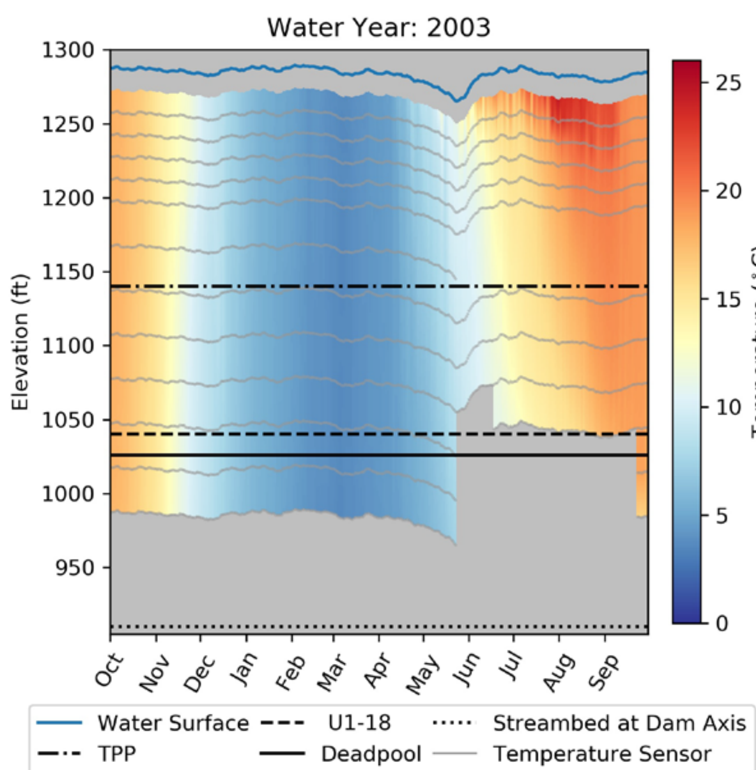


**Figure 5-15. Lake Roosevelt thermal stratification for water year 2003.**

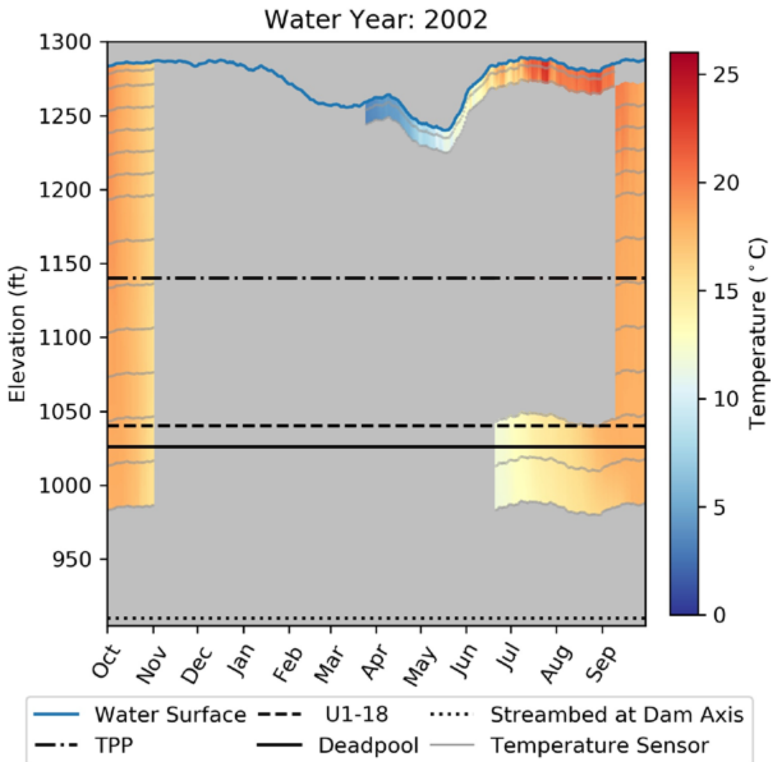


**Figure 5-16. Lake Roosevelt thermal stratification for water year 2002.**

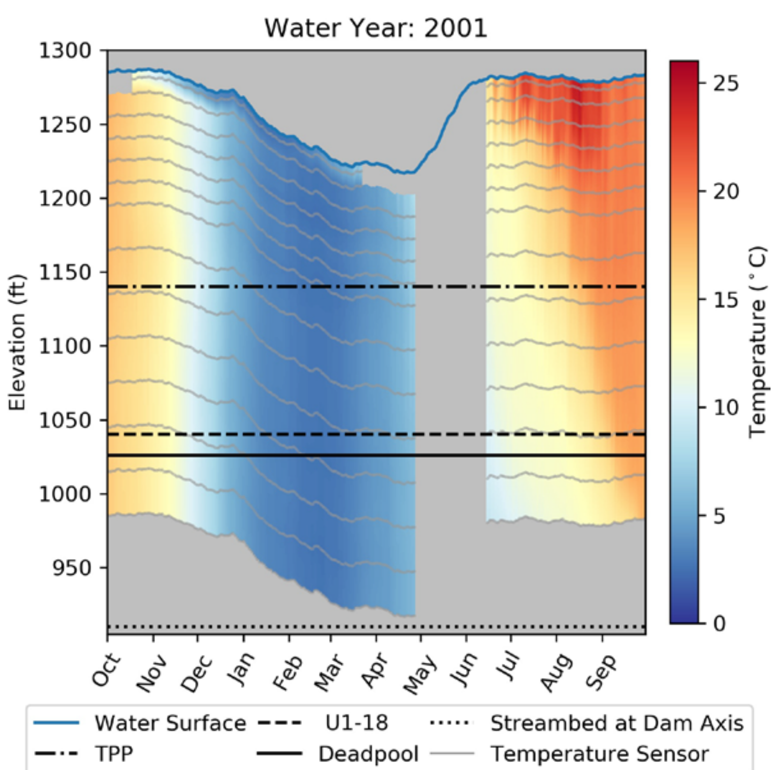


**Figure 5-17. Lake Roosevelt thermal stratification for water year 2001.**

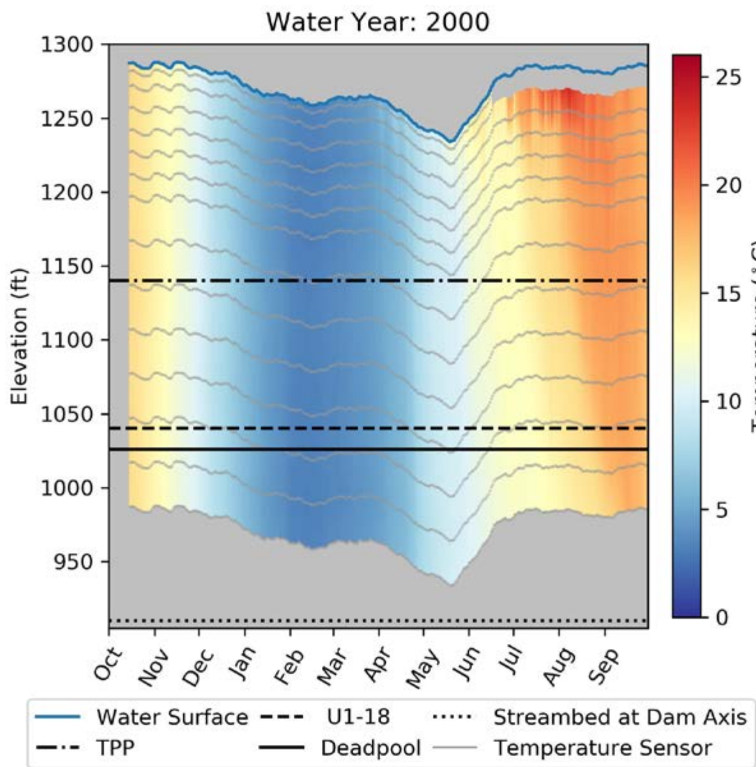


**Figure 5-18. Lake Roosevelt thermal stratification for water year 2000.**

Figure 2-19 through Figure 5-24 depict the temperatures (from 2015 to 2000) at the approximate forebay elevations of the intakes for the Left and Right Power plants (1,050 feet elevation is used here as an approximation of the pool temperature at this intake, at elevation 1,040 feet) and the Third Power Plant (1,150 feet elevation is used here as an approximation of the pool temperature at this intake, at elevation 1,140 feet). The difference demonstrates the same data as the thermal stratification figures but focus on the elevations of the reservoir that are most relevant to downstream temperatures. The small differences, combined with limited operational flexibility demonstrate very little potential to impact river temperatures downstream of Grand Coulee Dam.

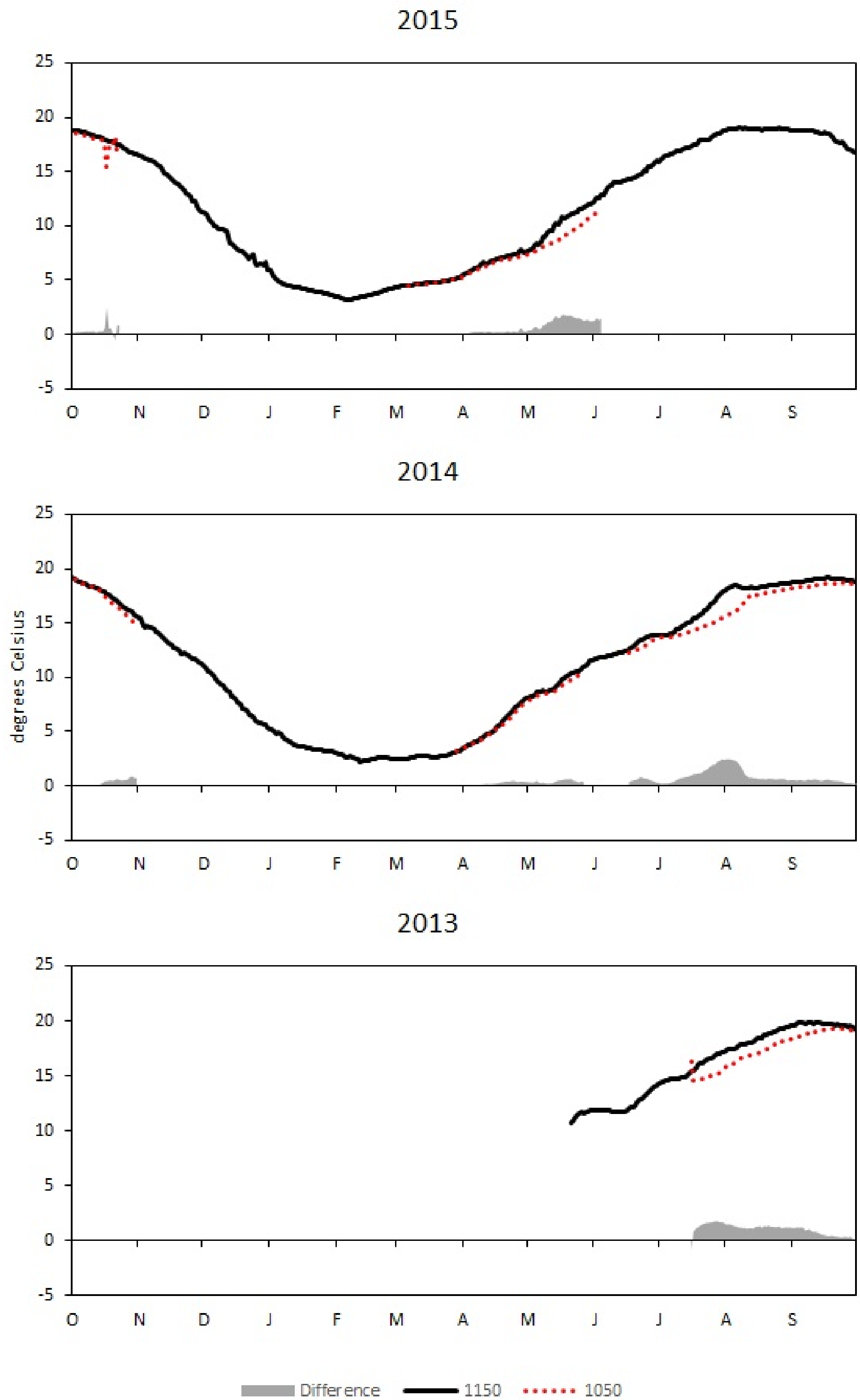


**Figure 5-19. Temperatures dating from 2015 to 2013 at the approximate forebay elevations of the intakes for the Left and Right Power Plants.**

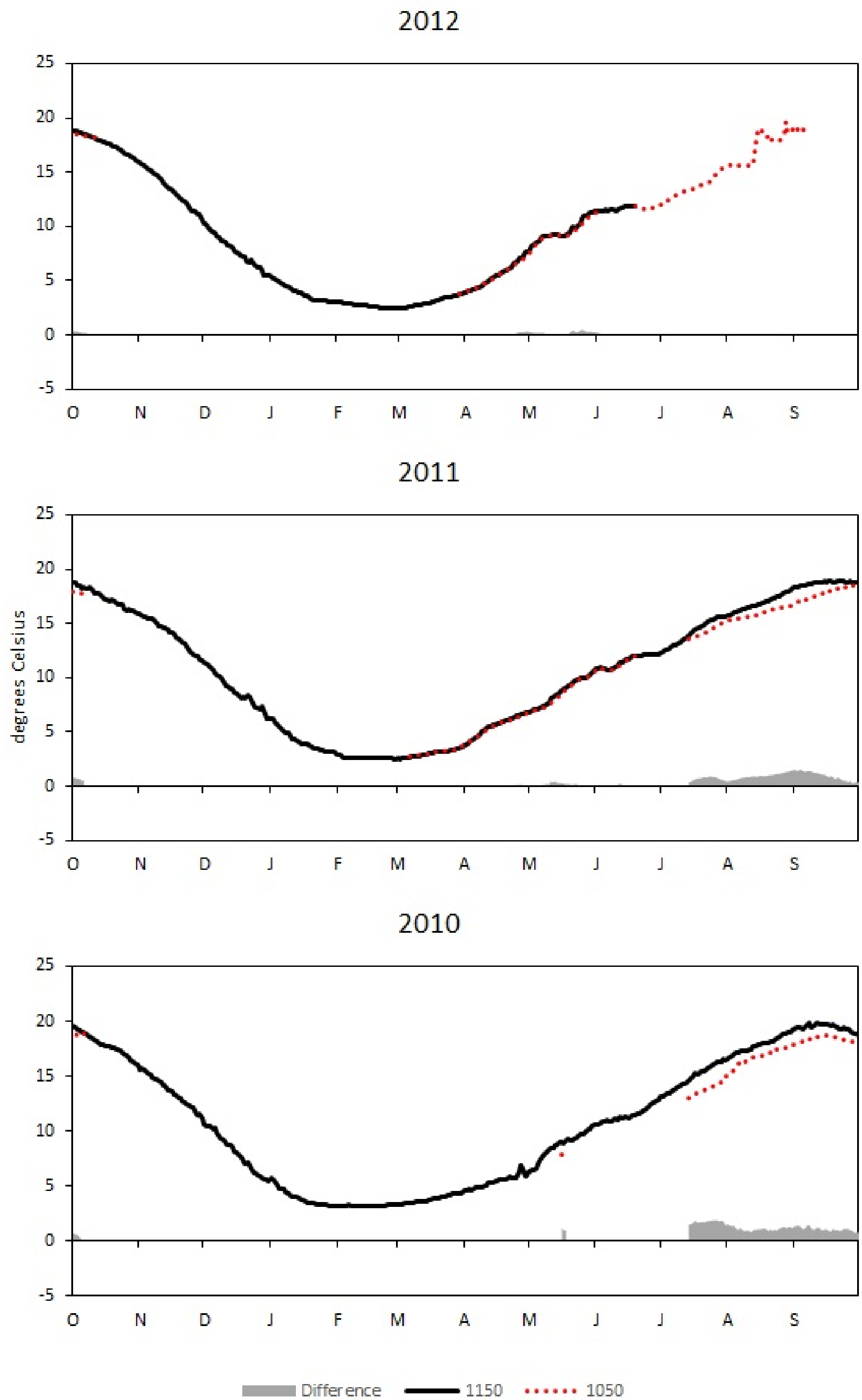


**Figure 5-20. Temperatures dating from 2012 to 2010 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**

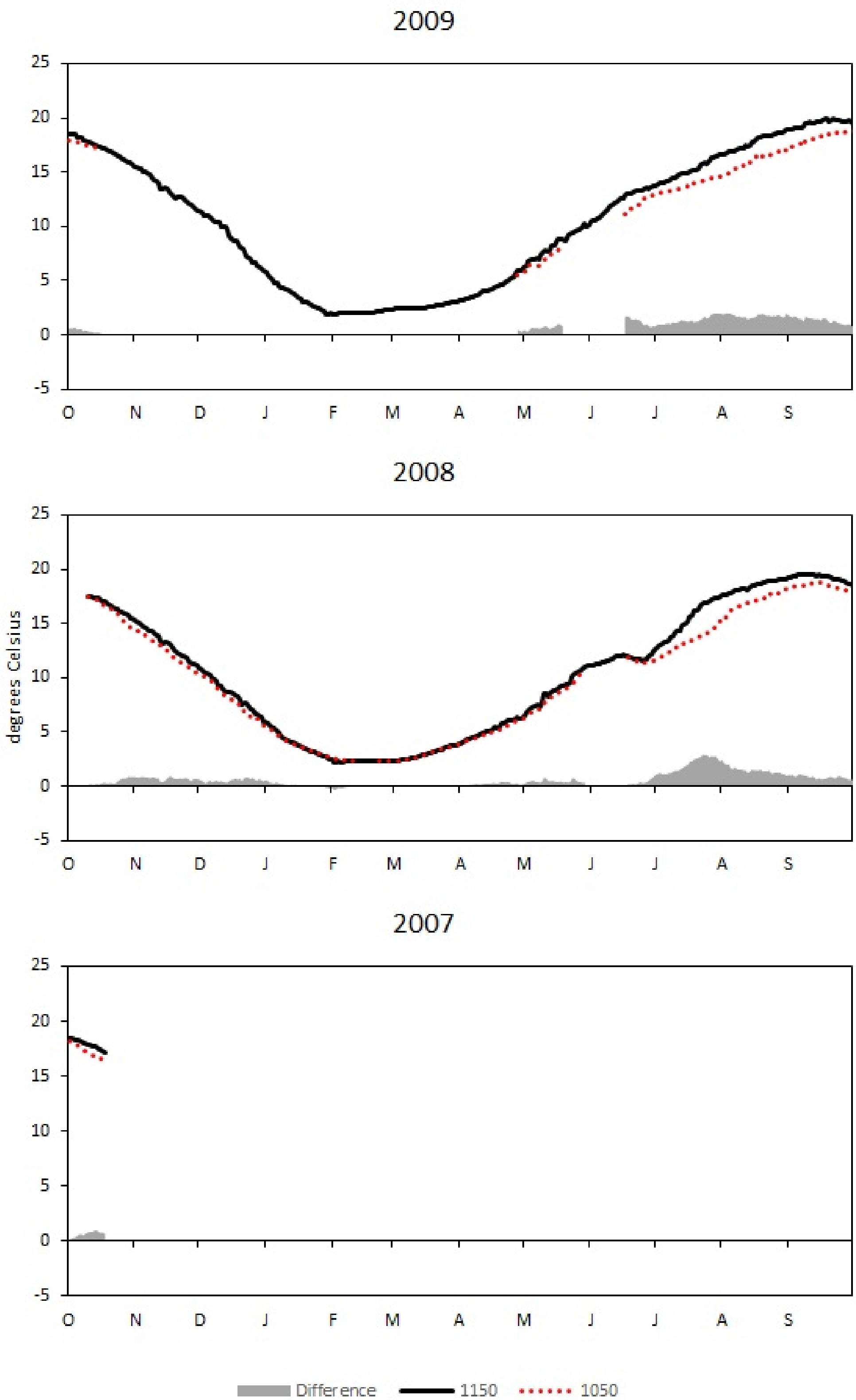


**Figure 5-21. Temperatures dating from 2009 to 2007 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**

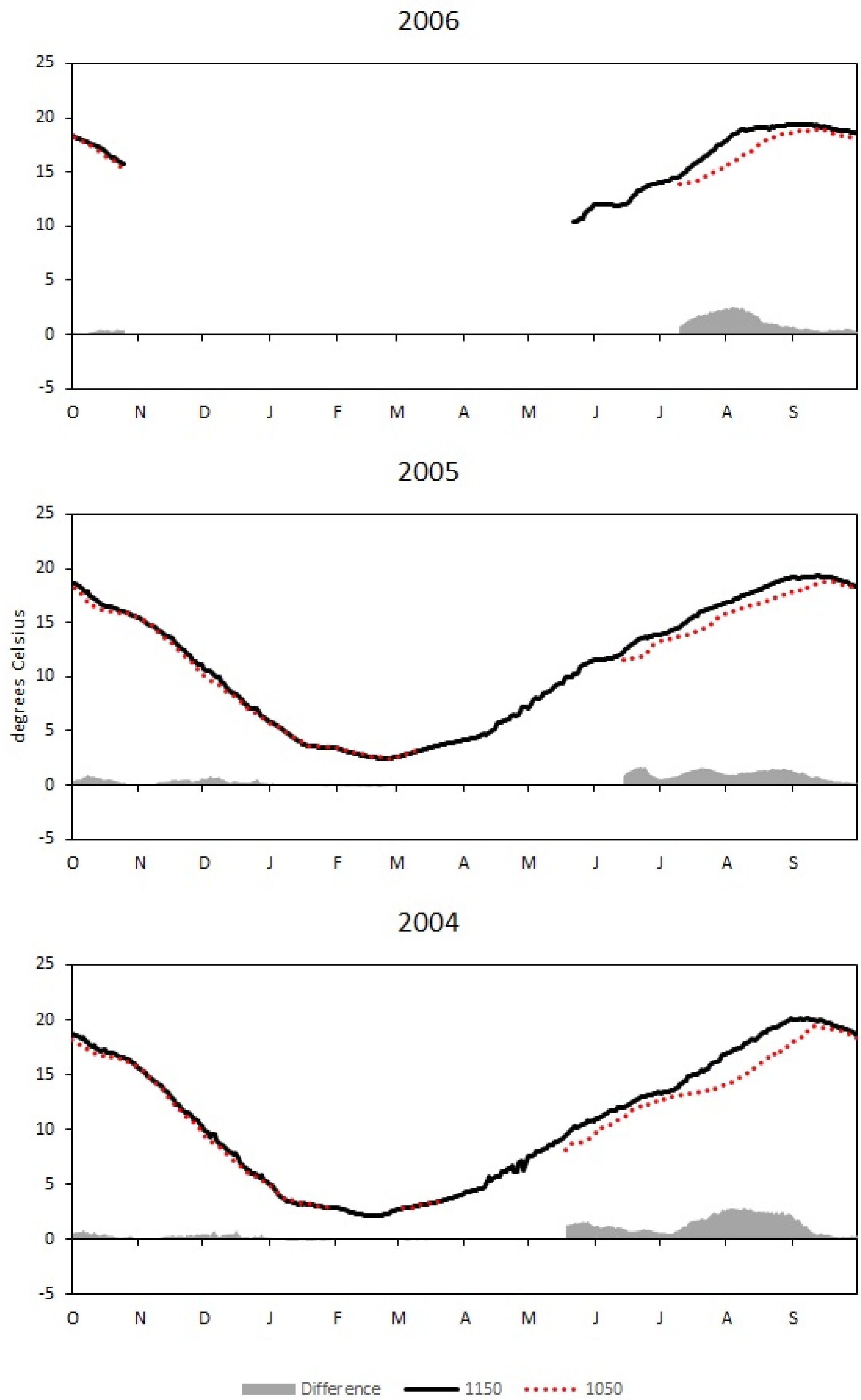


**Figure 5-22. Temperatures dating from 2006 to 2004 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**

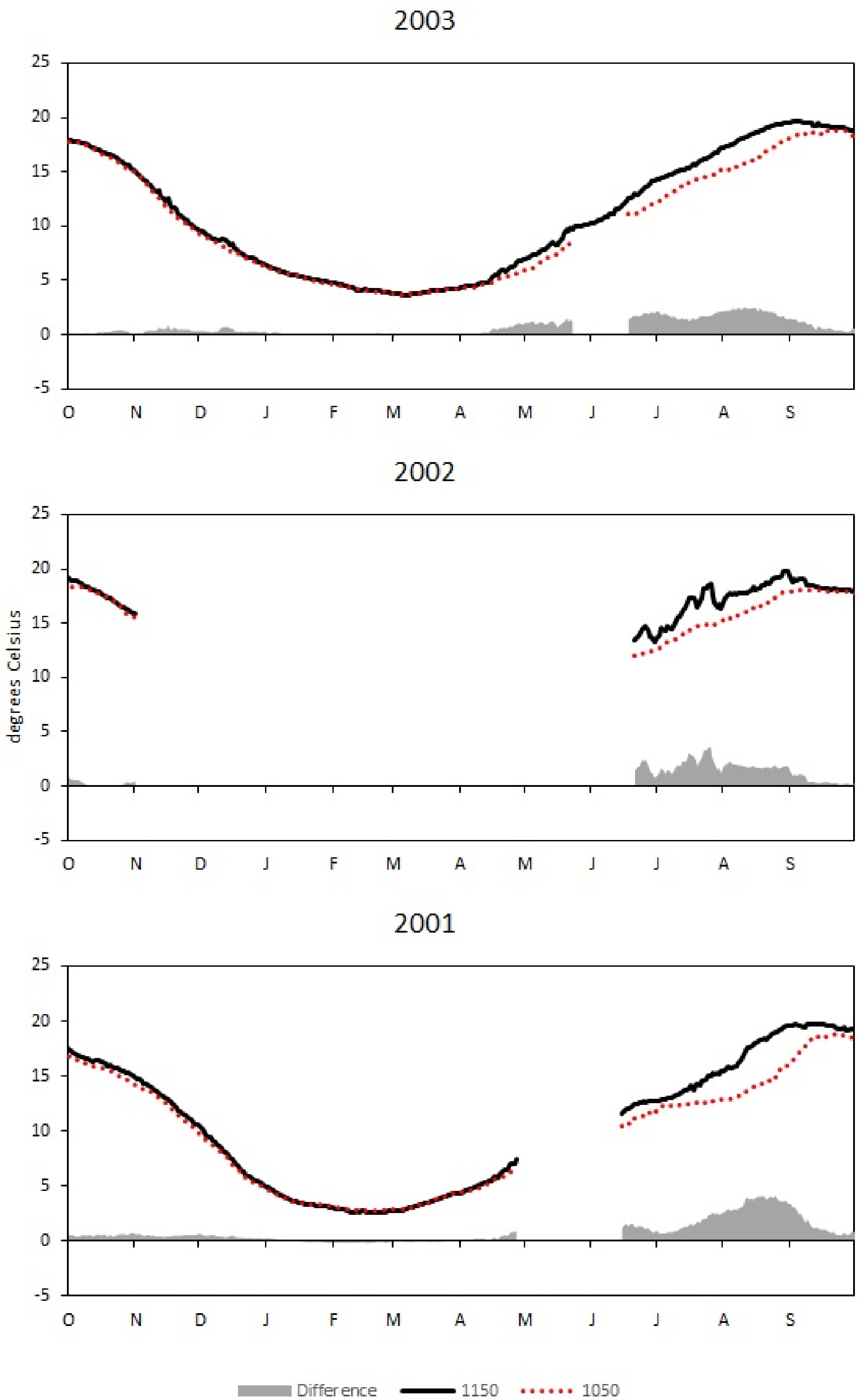


**Figure 5-23. Temperatures dating from 2003 to 2001 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**

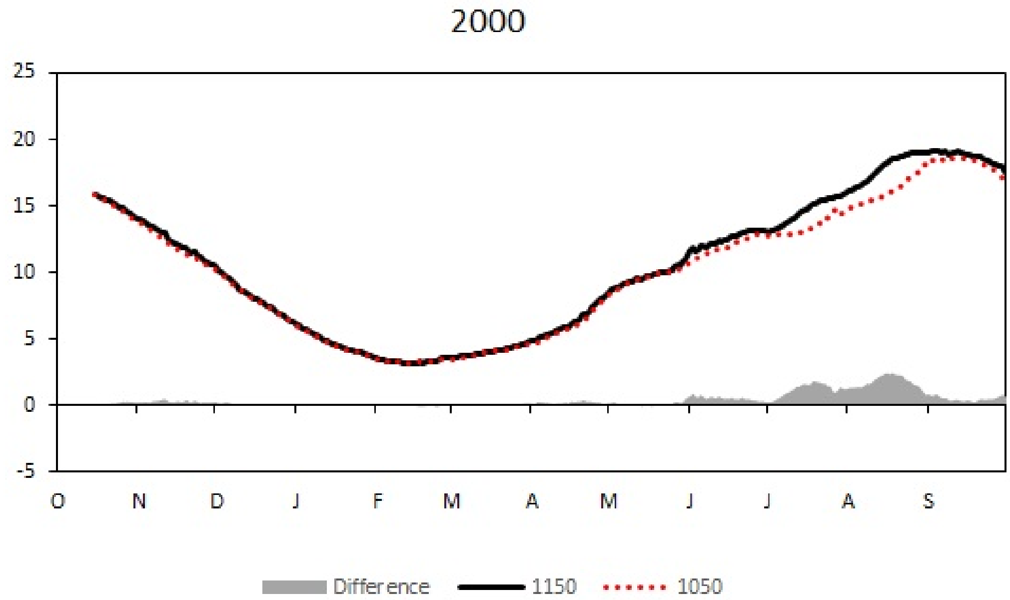


**Figure 5-24. Temperatures in 2000 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**

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RECLAMATION
*Managing Water in the West*

# Independent External Peer Review Report: Thermal Regime of the Columbia River at Lake Roosevelt

**U.S. Department of the Interior**
**Bureau of Reclamation**
**Pacific Northwest Regional Office**
**Boise, Idaho**

**August 2018**

## U.S. Department of the Interior

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

## Mission of the Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

# Table of Contents

# 1 PROJECT SUMMARY

The Pacific Northwest (PN) Region developed a white paper, *The Thermal Regime of the Columbia River at Grand Coulee Dam and Lake Roosevelt*, in response to regional requests to examine the potential for Grand Coulee to be operated to reduce downstream temperatures. These requests are based on a long-standing hypothesis in the region (outside of Reclamation) that the impoundment behind Grand Coulee (Franklin D. Roosevelt Reservoir, commonly referred to as Lake Roosevelt) could be used to help cool downstream water temperatures to benefit Endangered Species Act (ESA) listed salmon in the Columbia River. Reclamation began collecting temperature data in the reservoir in 2000. This data will contribute to a better understanding of what role Grand Coulee Dam could potentially play in reducing water temperatures in the Columbia River. The purpose of this paper presented for peer review is to examine data collected in Lake Roosevelt, as well as upstream and downstream of Grand Coulee Dam in the lower Columbia River, to characterize the current thermal regime. This paper also examines Grand Coulee Dam operational purposes and constraints, to provide a context to the regional request to use Grand Coulee to help cool water temperatures in the lower Columbia River.

The white paper is considered influential scientific information as defined by Office of Management and Budget Final Information Quality Bulletin for Peer Review (70 FR 2664-2677) and the Reclamation Manual Policy CMP P14 Peer Review of Scientific Information and Assessments. The nexus of this determination is that this document may provide a clearer understanding of the Columbia River thermal regime, opportunities or constraints at Grand Coulee Dam. There is potential that this information could inform ongoing processes in the basin, including the comprehensive Environmental Impact Statement (EIS) effort on the Columbia River System Operations being conducted by the Bureau of Reclamation, Army Corps of Engineers, and Bonneville Power Administration. Additionally, the information portrayed in this white paper may be useful to Environmental Protection Agency (EPA) for an anticipated need for a temperature Total Maximum Daily Load (TMDL) process for the Columbia River. This peer review is considered required based upon Reclamation Manual Policy CMP P14.

# 2 INDEPENDENT EXTERNAL PEER REVIEW PROCESS

The subject of this review is to consider the known information about the Columbia River at Grand Coulee Dam, including temperature data upstream, downstream and in the reservoir, to characterize the thermal regime of the Columbia River. This information combined with a discussion of project configurations and operations addresses questions concerning whether and to what extent operational changes of Grand Coulee could influence downstream water temperatures to benefit ESA listed salmon in the Columbia River.

The peer reviewers were selected based on experience (at least 10 years) with expertise in hydrology, water quality, and water management. They were identified as technical experts that understand Columbia River water temperature and associated processes, and that understand reservoir/system operations. Peer reviewers have education, professional experience, and peer recognition in their field, and have contributed to their field. Peer reviewers are external to Reclamation.

Three groups of peer reviewers were selected, peer reviewers are associated with Bonneville Power Administration (BPA), the Army Corps of Engineers (Corps), and Portland State University (PSU). For more details, including qualifications, see Appendix A.

# 3 RESULTS OF THE INDEPENDENT EXTERNAL PEER REVIEW

The draft report integrated most of the comments from peer reviewers (Appendix A), many were editorial, to improve the content of the final paper. See Appendix B for comments and responses.

# 4 APPENDIX A: REVIEWERS QUALIFICATIONS

Three groups of reviewers that have experience with Columbia River water quality and Columbia River System operations.

## 4.1 Bonneville Power Administration:

### 4.1.1 Kim Johnson, Environmental Engineer, PE

BPA Environmental Strategist (2015-Present)

- Policy Advisor and Technical Authority on Clean Water Act issues

Corps of Engineers, Northwestern Division, Environmental Engineer (2009-2013)

- NEPA and Water Quality Policy SME

EPA, Region 10 & Region 7, Environmental Engineer (1997-2008)

- Clean Water Act and Clean Air Act SME

Bureau of Reclamation, Great Plains Region, Civil Engineer (1992-1997)

- Water Resources, Design and NEPA SME

USDA Forest Service, Montana Civil Engineer (1988-1992)

- Design, NEPA and Contract Administration

### 4.1.2 Mildred Chenell, Operations Research Analyst

Water Resources Modeling Experience, 2013-2018

CE-QUAL-W2 Modeling Experience, 2018

MESM, Water Resources Management, UCSB, 2009

## 4.2 Army Corps of Engineers

### 4.2.1 Kathryn Tackley (title)

Kathryn Tackley is a Physical Scientist with the U.S. Army Corps of Engineers, Portland District, a position she has held for the last ten years. Prior to that, Kathryn worked as a contractor for the Corps of Engineers, Environmental Research and Development Center in Vicksburg, Mississippi. Her work experience ranges from the study of benthic macroinvertebrates in the Mississippi and Ohio Rivers to water temperature and total dissolved gas management in the Columbia, Snake and Willamette Rivers. From 2016-2017 she was on the Board of Directors for the Oregon Lakes Association. She currently sits on the Corps of Engineers Committee on Water Quality and is the Water Quality Technical Manager for the Columbia River System Operations Environmental Impact Statement.

## 4.3 Portland State University

### 4.3.1 Scott Wells, Ph.D, PE

Professor of Civil and Environmental Engineering, Portland State University, Portland, OR 97207-0751

wellss@pdx.edu; 503-725-4276

**Overview:** He has a Ph.D. from Cornell University in Civil and Environmental Engineering, and graduate and undergraduate degrees from MIT and Tennessee Technological University. Since 1987 he has been at Portland State University and is currently Professor of Civil and Environmental Engineering after serving for 12 years as Department Chair. His research areas are in modeling of environmental fluid mechanics: surface water quality and hydrodynamics and solid-liquid separation processes. He has written over 100 technical publications.

He has received 2 Fulbright scholar awards, one to the Ukraine and the other to Israel where he taught and did research at the Earth Institute at Hebrew University and at the Israeli Geologic Survey in Jerusalem, Israel. During that time he worked on the environmental impacts of the proposed Peace Conduit between the Gulf of Aqaba and the Dead Sea.

He is the co-author of the water quality and hydrodynamic model, CE-QUAL-W2, used throughout the world for temperature and water quality modeling studies or rivers, lakes and reservoir systems. He and his research team are active as peer-reviewers for the US EPA, State of California, the State Department, and many other organizations.

He regularly teaches classes in water quality and hydrodynamic modeling at Portland State University, as well as workshops on modeling CE-QUAL-W2. He has presented an EPA sponsored webinar to a national audience on the Impact of Sediments on Water Quality, was an invited participant to EPA Region 6 workshop on water quality modeling, and was selected by EPA to serve on the Cayuga Lake Technical TMDL Review Team.

He has been a frequent invited seminar speaker and keynote speaker at conferences in the US and abroad (China, Netherlands, Brazil) and is currently a Principal Investigator for the Collaborative Center for Geo-hazards and Eco-Environment in Three Gorges Area, Hubei Province, Three Gorges University, Yichang, China.

**Expertise:** Environmental fluid mechanics: surface water quality and hydrodynamics and solid-liquid separation processes.

**Experience in surface water quality and hydrodynamic studies:** He has been involved in over 100 water body studies. In *Oregon*, he has been involved in hydrodynamic/water quality modeling on the Tualatin River, Hagg Lake, the Columbia Slough system (Lower Columbia Slough, Upper Columbia Slough, Smith and Bybee Lakes, Peninsula Canal), Klamath River, Russel Creek (near Eugene), Coast Fork of the Willamette River, Bull Run Reservoir #2, Bull Run Reservoir #1, Bull Run Reservoir #3, Bull Run Lake, Upper and Lower Bull Run River, Willamette River (Oregon City Falls to Columbia River, including Multnomah Channel, Willamette River basin), Johnson Creek, Ashland Creek, Cooper Creek Reservoir, Skipanon River, Schooner Creek, Siletz Bay, South Santiam River, Middle Fork Willamette River, Bear Creek, Stone Creek below Timothy Lake, Laurance Lake, Waldo Lake, South Slough off Coos Bay, Yaquina Bay and Yaquina River, the Clackamas River Basin (Clackamas River, Timothy Lake, Lake Harriet, Frog Lake, North Fork Reservoir, Faraday Lake, Estacada Lake) and areas of Tillamook Bay and the Columbia River (Bonneville Dam to St. Helens). His experience also includes water quality and hydrodynamic studies in *Hawaii* (Wahiawa Reservoir), Virginia (N. Anna Reservoir), *Tennessee* (Center Hill Lake), *Kentucky* (Laurel River Reservoir), *Idaho* (Boise River, Lower Snake River from Brownlee Reservoir to C. J. Strike Reservoir, Brownlee Reservoir, C. J. Strike Reservoir, Spokane River, Oxbow Reservoir, Hells Canyon Reservoir, Coeur D'Alene Lake, Pend Oreille River and Lake), *California* (Folsom reservoir, Oroville Thermalito diversion pool, Klamath River, Philbrook Reservoir, DeSabla Reservoir, Butte Creek, Millerton Lake, Lake Spaulding, Bowman Lake, Rollins Reservoir, Fordyce Reservoir, Jackson Meadows Reservoir), *Washington* (Columbia River, Clear Lake, Spirit Lake, Spokane River, Long Lake, White and Puyallup Rivers, Snohomish River and Estuary, Green River, Lake Roosevelt, Chelan River, Pend Oreille River, Tolt Reservoir, Lake Chaplain, Budd Inlet/Capitol Lake/Deschutes River, Chester Morse Reservoir, Cedar River, Banks Lake, Keechelus Reservoir, Kachess Reservoir), *Colorado* (Cherry Creek Reservoir), *Wisconsin* (Kinnickinnic River, Lake George), *North Carolina* (Jocassee and Keowee Reservoirs), *Oklahoma* (Tenkiller Reservoir on the Illinois River, Eucha Reservoir, Spavinaw Reservoir), Texas (Lake Lavon, Lake Travis), *Florida* (Tampa Bay Water Supply Reservoir, Reservoir C-44), *Montana* (Warm Springs Ponds, Butte, MN) , *New York* (Conesus, Hemlock, Cayuga, and Honeoye Lakes*), West Virginia, Pennsylvania, Ohio* (Ohio-Alleghany-Monongahela Rivers), *China* (Three Gorges Reservoir), *Spain*, *Peru* (Chaglla Reservoir), *Brazil* (Tabajara Reservoir), *Guyana* (Amaila Reservoir), *Costa Rica*, *Canada* (Lake Lagopede, Pit Lakes region lakes), *Israel* (Lake Kinneret or Sea of Galilee, Jordan River, Dead Sea, experimental ponds at Dead Sea Works), and in the *Ukraine* (Dnieper River-reservoir system and Kiev Sea).

**Education:** Ph.D. Cornell Univ.; S.M. MIT; BSCE Tennessee Technological Univ., P.E. in Civil Engineering and in Environmental Engineering

**Reviewer**: National Science Foundation Research Proposals, USGS Water Resource Research Institute Proposals, Fluid/Particle Separation Journal, Powder Technology, Separations Technology, Separation Science and Technology, Journal of Environmental Engineering ASCE, Journal of Geotechnical Engineering ASCE, Journal of Hydrologic Engineering ASCE, Journal of Hydraulic Engineering ASCE, Journal of Irrigation and Drainage ASCE, Environmental Science and Technology, Water Resources Research, International Journal of Heat and Mass Transfer, Estuarine, Coastal and Shelf Science, Journal of HydroInformatics, American Society of Agricultural and Biological Engineers.

**Partial list of research and consulting partners:** METRO (Portland); Rhone-Poulenc Chemical Company; State of Oregon; Scientific Resources, Inc.; OBEC Consulting Engineers; AMTRAK; EWEB; Woodward-Clyde Consulting Engineers; Fishman Environmental Services;

Black/Veatch; Cornforth Consultants, Inc; HDR Engineering, Inc; CH2MHill; Carollo Engineers; SECOR; R. M. Towill Corporation; LimnoTech, Inc; City of Bremerton; EPA; City of Sutherlin, OR; Lincoln City, OR; Tulalip Indian Tribes; Portland General Electric; City of Portland; Washington Department of Ecology; Israeli Geologic Survey; Idaho Power Company, AVISTA Corporation; USBLM; US BurRec; PacifiCorp; Chelan Public Utility District; City of Kansas City; Pacific, Gas and Electric Company; Stormwater Management 360; City of Toledo; MWH Engineering; HyQual Engineering; Waterways Experiments Station (Corps of Engrs); Corps of Engrs (Portland District); Oregon DEQ; Idaho DEQ; Friends of Blue Lake; King County (WA); Clackamas County (OR), CRITFC, US Forest Service; CDS Inc.; Clackamas River Water Supply group; Middle Fork Irrigation District; USGS; West Consultants, Seattle, WA; ConTech Inc., Portland, OR.

**Selected publications:** Dr. Wells' publications have appeared in the following Journals: Aquatic Ecology, Ecological Modeling, Water Resources Bulletin, ASCE Journal of Hydraulic Engineering, Research Journal of the Water Pollution Control Federation, Fluid/Particle Separation Journal, ASCE Journal of Environmental Engineering, Water Research, Water Environment Research and have appeared in Proceedings for the following conferences: ASCE World Water and Envir. Resources, Water Resources and Envir. Engr., WEF National TMDL Science and Policy, International Reservoir Limnology and Water Quality, Federal Interagency Hydrologic Modeling, IAHR Hydroinformatics, Ecohydraulics, American Filtration Society, and American Bar Association Water Law conferences. He also has written almost 100 technical reports. A full-list can be found at http://www.cee.pdx.edu/~scott. A selected list of publications since 2005 are shown below:


Al-Zubaidi, H. A. M., and Wells, S. A. (2018) "3D Hydrodynamic and Water Quality Model Development and Verification in Surface Water Bodies", Journal of Hydraulic Research, in-print.

Berger, C. and Wells, S. (2017) "Modeling the Impact of Water Quality and Food Web Structure on Bull Trout in Two Washington Reservoirs," ASCE EWRI Congress, Sacramento, May.

Van Glubt, S., Wells, S., and Berger, C. (2017) "Hydrodynamic and Water Quality Modeling of the Chehalis River in Washington," ASCE EWRI Congress, Sacramento, May.

Al-Murib, M., Wells, S., and Talke, S. (2017) "Estimation of Surface Water Temperature of the Tigris River System in Iraq," ASCE EWRI Congress, Sacramento, May.

Al-Zubaidi, H. A. M., and Wells, S. A. (2017) "3D Numerical Temperature Model Development and Calibration for Lakes and Reservoirs: A Case Study, ASCE EWRI Congress, Sacramento, May.

Daobin, J, Wells, S. A., Yang, Z., Liu, Defu, Huang, Y., Ma, J. and Berger, C. (2017) "Impacts of water level rise on algal bloom prevention in the tributary of Three Gorges Reservoir, China," Ecological Engineering, Volume 98, January 2017, Pages 70-81.

Wells, S. and Berger, C. (2016) “Modeling the Response of Dissolved Oxygen to Phosphorus Loading in Spokane Lake,” Lake and Reservoir Management, 32:3, 270-279, (DOI:10.1080/10402381.2016.1211910).

Annette B.G. Janssen, George B. Arhonditsis, Arthur Beusen, Karsten Bolding, Louise Bruce, Jorn Bruggeman, Raoul-Marie Couture, Andrea S. Downing, J. Alex Elliott, Marieke A. Frassl, Gideon Gal, Daan J. Gerla, Matthew R. Hipsey, Fenjuan Hu, Stephen C. Ives, Jan H. Janse, Erik Jeppesen, Klaus D. Jöhnk, David Kneis, Xiangzhen Kong, Jan J. Kuiper, Moritz K. Lehmann, Carsten Lemmen, Deniz Özkundak, Thomas Petzoldt, Karsten Rinke, Barbara J. Robson, René Sachs, Sebastiaan A. Schep, Martin Schmid, Huub Scholten, Sven Teurlincx, Dennis Trolle, Tineke A. Troost, Anne A. Van Dam, Luuk P.A. Van Gerven, Mariska Weijerman, Scott A. Wells, Wolf M. Mooij (2015) “Exploring, exploiting and evolving diversity of aquatic ecosystem models: a community perspective”, Aquatic Ecology, Volume 49, Issue 4, 513-548, DOI 10.1007/s10452-015-9544-1.

Ma, Jun; Liu, Defu; Wells, Scott A.; Tanga, Hongwu; Jif, Daobin; Yang, Zhengjian (2015) “Modeling density currents in a typical tributary of the Three Gorges Reservoir, China”, Ecological Modeling, Volume 296, 24 January 2015, Pages 113–125, doi:10.1016/j.ecolmodel.2014.10.030

Berger, C. J., Bigham, G., and Wells, S. A. (2014) “Prediction of GHG Emissions from a New Reservoir,” Proceedings World Environmental and Water Resources Congress, EWRI, ASCE, Portland, OR, pp. 1010-1019.

Martinez, V. I., Wells, S. A. and R. C. Addley (2014) “Meeting Temperature Requirements for Fisheries Downstream of Folsom Reservoir, California,” Proceedings World Environmental and Water Resources Congress, EWRI, ASCE, Portland, OR, pp. 1081-1092.

Shoajei, N. and Wells, S. A. (2014) “Automatic Calibration of Water Quality Models for Reservoirs and Lakes,” Proceedings World Environmental and Water Resources Congress, EWRI, ASCE, Portland, OR, pp. 1020-1029.

Wells, S. A. (2014) “Integrating Fish Bioenergetics and Volitional Movement in Water Quality and Hydrodynamic Models,” Proceedings Water Environment Federation Conference, New Orleans, September 2014.

Berger, C. J.; Wells, S. A..; and Wells, V. (2012) "Modeling of Water Quality and Greenhouse Emissions of Proposed South American Reservoirs," Proceedings of the 2012 World Environmental & Water Resources Congress, Albuquerque, New Mexico, May 20-24, 2012, pp. 911-923.

Wells, S. A..; Wells, V., and C. J. Berger (2012) " Impact of Phosphorus Loading from the Watershed on Water Quality Dynamics in Lake Tenkiller, Oklahoma, USA," Proceedings of the 2012 World Environmental & Water Resources Congress, Albuquerque, New Mexico, May 20-24, 2012, pp. 888-899.

Wells, V. I. and Wells, S. A. (2012) “CE-QUAL-W2 Water Quality and Fish-bioenergetics Model of Chester Morse Lake and the Cedar River,” Proceedings World Environmental and Water Resources Congress, EWRI, ASCE, Albuquerque, NM, pp. 2756-2767.

Mooij WM, Trolle D, Jeppesen E, Arhonditsis G, Belolipetsky PV, Chitamwebwa DBR, Degermendzhy AG, DeAngelis DL, De Senerpont Domis LN, Downing AS, Elliott JA, Fragoso Jr CR, Gaedke U, Genova SN, Gulati RD, Håkanson L, Hamilton DP, Hipsey MR, ‘t Hoen J, Hülsmann S, Los FJ, Makler-Pick V, Petzoldt T, Prokopkin IG, Rinke K, Schep SA, Tominaga K, Van Dam AA, Van Nes EH, Wells SA and Janse JH (2010) “Challenges and opportunities for integrating lake ecosystem modelling approaches,” Aquatic Ecology:DOI:10.1007/s10452-010-9339-3,44(3):633-667.

Cheslak, E; Berger, C; Annear, R., and Wells, S. (2009) “Protecting Spring-Run Chinook Salmon: The Use of a Two-dimensional Water Temperature Model to Evaluate Alternative Hydroelectric Operations,” WaterPower XVI Proceedings, Spokane, WA, July 27-30, 2009

Berger, C.; McKillip, M.; Annear, R.; Wells, V., and Wells, S. (2009) “Modeling the Spokane River-Lake Roosevelt System,” Proceedings IAHR 33rd Congress, Vancouver, BC, August 9-14, pp. 6223-6230.

Berger, C. and Wells, S. (2008) “A Macrophyte Water Quality and Hydrodynamic Model,” ASCE, Journal of Environmental Engineering, Volume 134, Issue 9, pp. 778-788 (September 2008).

Wells, S. A., J. R. Manson, and J. L. Martin (2007) “Numerical Hydrodynamic and Transport Models for Reservoirs,” Chapter 4 in Energy Production and Reservoir Water Quality, ASCE.

Annear, R. L., and S. A. Wells (2007), A comparison of five models for estimating clear-sky solar radiation, Water Resour. Res., 43, W10415, doi:10.1029/2006WR005055.

Berger, C. J. and Wells, S. A. (2007) "Development and Calibration of Lake Whatcom Water Quality Model," Proceedings of the Water Environment Federation TMDL Conference, Seattle, WA, June 24-27.

Berger, C. J. and Wells, S. A. (2007) "Modeling Effects of Channel Complexity and Hyporheic Flow on Stream Temperatures," Proceedings Water Environment Federation TMDL Conference, Seattle, WA, June 24-27.

McKillip, M. and Wells, S. (2006) “Hydrodynamic, water quality and fish bioenergetics modeling in Lake Roosevelt Washington USA using CE-QUAL-W2,” Proceedings, 5th International Conference on Reservoir Limnology and Water Quality, Brno, Czech Republic, August 27-September 2.

Harrison, J. R.; Wells, S. A.; Rychert, R. C.; Naymik, J. (2005) “Searching For A Practical Approach To Partition Biomass And Detritus For Ecological Models Applied To The

Snake River And Its Reservoirs," Proceedings ASLO Conference, Salt Lake City, UT, February 24-25.

Wells, S. A. (2005) "Use and Misuse of Computer Models in Water Disputes," Proceedings American Bar Association 23rd Annual Water Law Conference, San Diego, CA.

### 4.3.2 Chris Berger, Ph.D., PE

Research Assistant Professor, Department of Civil and Environmental Engineering, Portland State University

**Expertise:** Water Quality and Hydrodynamic Modeling; Development and application of CE-QUAL-W2 water quality model; Ground Water Modeling; Computer Programming; Water Quality Sampling; Environmental Data Analysis

**Experience:** Currently participating in the development of CE-QUAL-W2 water quality models. Responsibilities include computer programming, model calibration, water quality sampling, analysis of management scenarios, and the development of specialized macrophyte/epiphyton/algal and culvert simulation algorithms. Contributed to the development of water quality models of the Tualatin River, Oregon; Columbia Slough, Oregon; Willamette River, Oregon; Lake Whatcom, Washington; Cooper Creek Reservoir, Oregon; Spokane River, Washington; Lake Whatcom, Washington; Laurance Lake, Oregon; the Snake River, (Brownlee Reservoir, Hells Canyon Reservoir, and Oxbow Reservoir) Idaho; and Wahiawa Reservoir, Hawaii. He was a contract worker with the U. S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi (October, 1996 to December, 1996) and conducted literature review of biological and chemical rate coefficients used in water quality modeling. He worked as a Junior Engineer for Mackenzie Engineering Incorporated, Portland (June, 1991 to December, 1991, site development work including the design of storm sewers, sanitary sewers, roads, parking lots, and water utilities) and was Assistant Watermaster for the Tualatin River District in Washington County. Oregon (June, 1990 to September, 1990, measured stream flows, maintained stream gaging stations, helped regulate water rights, surveyed stream gaging sites, and inspected wells in the Tualatin River basin). Author of over 35 technical reports and 9 publications.

**Education:** PhD. ESR/CE, Portland State University; MS CE, PSU, BS Civil Engineering, PSU; BS Physics, Oregon State University.

**Professional registration:** Professional Engineer, P. E., Oregon #48590, Civil Engineering

**Reviewer:** Hydrobiologia; Jour. of the North American Benthological Society; Jour. of Hydrological Engineering; Water Resources Research

**Selected Publications:**

Berger, C. and Wells, S. (2017) “Modeling the Impact of Water Quality and Food Web Structure on Bull Trout in Two Washington Reservoirs,” ASCE EWRI Congress, Sacramento, May.

Van Glubt, S., Wells, S., and Berger, C. (2017) “Hydrodynamic and Water Quality Modeling of the Chehalis River in Washington,” ASCE EWRI Congress, Sacramento, May.

Wells, S. and Berger, C. (2016) “Modeling the Response of Dissolved Oxygen to Phosphorus Loading in Spokane Lake,” Lake and Reservoir Management, 32:3, 270-279, (DOI:10.1080/10402381.2016.1211910)

Berger, C. J.; Bigham, G. N..; and Wells, S. A. (2014) Prediction of GHG Emissions from a New Reservoir," Proceedings of the 2014 World Environmental & Water Resources Congress, Portland, Oregon, June 1-5, 2014.

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# APPENDIX B: TABLES OF REVIEW COMMENTS AND RESPONSES.

**Review of Thermal Regime of the Columbia River at Lake Roosevelt**
**(April 2016)**

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| M. Chennell | 1 | 2 | Warm water events affect many species, not just anadromous | Insert “and other” prior to “species” | Adopted |
| K. Johnson | 1 | 5 | Report is looking at ability to influence water temp in future | Replace “have been” with “be” | Adopted |
| K. Johnson | 1 | 6-10 | Sentences starting with “Some storage reservoirs..” are awkward, and the references to lake behavior here are confusing. | Recommend revising to focus on stratification and ability to release cool water to mitigate downstream temperatures. | Adopted |
| M. Chennell | 1 | 9 | Odd phrasing | Strike “much of their” | Adopted |
| K. Johnson | 1 | 34-37 | Outflow water temperatures are also highly influenced by inflow temperature. | Recommend adding the concept of inflow temps and boundary conditions. | Adopted |
| M. Chennell | 3 | 61 | Might say in text that temp control often to release warmer water… | …noted in footnote on line 77 | Adopted |
| K. Johnson | 3 | 71-73 | “data” and “near the dam” is repeated in this sentence. Also it would be helpful to provide more detailed information. | Recommend rewording to say something like, “The data was collected using a string of temperature loggers at different depths from 2000-2016 to document the thermal conditions of Lake Roosevelt near the dam.” | Adopted |
| K. Johnson | 4 | 90 | There are actually 31 federal dams in the Federal Columbia River “Power System.” Figure 2-2 also shows some of the federal non-power | May want to use a different map, or revise the language to be consistent with Figure 2-2. | Noted |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| | | | dams – so the number of federal dams on this map is >31. | | |
| M. Chennell | 4 | 92 | Flood risk mitigation | Change to Flood risk management | Adopted |
| K. Johnson | 7 | 117 | “As shown by Table 2-1.” Is not a sentence | Edit | Adopted |
| M. Chennell | 7 | 123 | M&I abbreviation should be used earlier | Use on pg 4, line 84, read “M&I water supply” | Adopted |
| M. Chennell | 7 | 128+ | Table: 3rd column label: kcfs, 5th column label superscript 2 looks… | Like squared. | Adopted |
| K. Johnson | 8 | 140 | Note in last row of table has a single “(“ | | Adopted |
| K. Johnson | 8 | 145 | “warm” is a relative statement | Recommend replacing “warm” with “warmer” | Adopted |
| K. Johnson | 9 | 154-159 | This description is confusing – slightly lower in July and then later in summer shifts to cooler. | Recommend revising to say “starting in July outflows are cooler” or adding more detail for the later in the summer (months and temp difference). | Adopted |
| M. Chennell | 9 | 157 | Patter should read pattern | Edit | Adopted |
| M. Chennell | 9 | 160 | Figure 2-3 missing a key. | Add key | Adopted |
| K. Johnson | 10 | 176-179 | Temperature data is available for Priest Rapids and other mid-C dams (year round) at the follow website: http://pweb.crohms.org/ftppub/water_quality/tdg/ | May want to replace “Presumable” with a reference to the site and update the language that data is limited. | Adopted |
| K. Johnson | 10 | 180 | Sentence is awkward | Add “to” between Dam and Pasco, WA and possibly add a reference to Table 2-3. | Adopted |
| M. Chennell | 11 | 188 | Confusing to include Clearwater data here | Wait until discussing Dworshak | Adopted |
| M. Chennell | 11 | 201 | Extra close paren | Remove | Adopted |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| K. Johnson | 11 | 208 | The Mid-Cs are not technically "privately-owned," but rather are owned by "Public Utility Districts." | Replace "privately owned," with something a little more accurate – since line 175 already identifies the dams, maybe just keep the same PUD reference. | Adopted |
| K. Johnson | 11-13 | 197-217 | Is there a reason that 2009 was chosen for this discussion? | Add why 2009 if there is a reason. | This year was selected as just an example year – typical ops, thermal situation. Added explanatory sentence. |
| K. Johnson | 15 | 251-260 | It would be interesting to add a sentence or two about the Columbia River sockeye in 2015, since they migrated through the river below Grand Coulee | Language should be readily available in the NOAA report. | Added language about Columbia River Sockeye in 2015.l |
| K. Johnson | 15 | 263 | Typo 2-9 x 2 | | Adopted |
| M. Chennell | 22 | 341 | Not sure key is helpful. | Explain U1-18 (Units 1-18=L&R PHs), etc. | Added explanation. |
| M. Chennell | 23 | 357 | Add "of  Grand Coulee Dam" after "configuration" | Edit | Adopted |
| K. Johnson | 23 | 363 | Recommend adding a reference to the Vernita Bar Agreement | | Adopted |
| K. Johnson | 23 | 367 | Footnote 7 – says successfully winter operations | | Adopted |
| M. Chennell | 24 | 384 | Define TMT | Also, add to list of Acronyms | Adopted |
| M. Chennell | 25 | Ftnt. | Unclear PP vs PH.  Earlier PH was used.  Be consistent | Plant for Project, House for Sub-Project? | Used power plant to be consistent with other Reclamation documents. |
| K. Johnson | 25 | 413 | Recommend deleting references to voluntary and involuntary spill – not relative to this discussion re: Grand Coulee operations. | | Adopted |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| K. Johnson | 25 | 414-415 | The actual TDG water quality standards are established by the states and approved by EPA. | Recommend deleting the Clean Water Act sentence and add “consistent with state water quality standards.” After coordinated together to minimize TDG in the following sentence. | Adopted |
| M. Chennell | 25 | 417 | Add “system” before “TDG” & “with forebay elevation” prior to … | “below 1265.5” | Adopted |
| M. Chennell | 25 | 420-2 | Remove parens, replace significant with “as much” or something… | Edit | Adopted |
| K. Johnson | 25 | 420 & 422 | Repetitive language in these lines referring to drum gates not generating significant TDG | Recommend deleting the first reference in parenthesis. | Adopted |
| M. Chennell | 22-6 | All | Edit for consistent voice with other parts of the paper. | Edit | Adopted |
| M. Chennell | 26 | 446 | This section seems to require a new heading (not summer specific) | Add Heading | Adopted |
| K. Johnson | 27 | 461 | Does this operation represent a specific year or just a typical year | Add language | Adopted |
| K. Johnson | 28 | 466 | This sentence sounds like all the constraints prevent operation of the Dam | Revise language to read constraints effect the operational flexibility. | Adopted |
| K. Johnson | 28 | 468-487 | This section seems to be answering a question about operational flexibility that would help with temperature, but up to this point all the data says there is no cool water available even if there was flexibility to modify operations. | May be helpful to spell out the flexibly operations question at the beginning of this section and then show that operational flexibility is limit even if there was cool water available. | We wanted to make both points, that cool water is not available and the project is highly constrained operationally. |
| M. Chennell | 28 | 490 | “is provided to provide” repetitive | Edit | Adopted |
| M. Chennell | 29 | 522 | Remove extra close paren | Edit | Adopted |
| M. Chennell | 32-3 | All | These are the same graph. Why include both | Remove one of the graphs | Adopted |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| M. Chennell | 34 | Fig | Add key, also add DWR release temps or something for context | | Adopted |
| M. Chennell | 28-34 | All | Work on comparison DWR to GCL. Specific Temps? Tables? | Inflow/Outflow? Feels lacking a bit… | We added to the DWR comparison section, but don't want to over-emphasize this section. |
| M. Chennell | 46 | 658+ | What does invert elevation mean? | | Added language to clarify. |
| M. Chennell | 47-52 | All | These seem to show greater than 1 degree dif. I'd hesitate to use | | We left in, reporting all available information. |
| | | | As folks may want to cut off all 3rd PH gen in times of high temps. | | Not possible due to operational constraints. |

**Review of Thermal Regime of the Columbia River at Lake Roosevelt (April 2016)**

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| Tackley | 1 | 6-7 | Confusing sentence; consider revising. | *USBR edit: Storage reservoirs that have the ability to mitigate increasing temperatures exhibit thermal stratification and behave similar to lakes.* | Adopted |
| | 11 | 186 | Table 2-3. Is this table showing the monthly average of the mean daily river temperatures? If mean daily, then why is there only one reading per month? | Fixed to state Median monthly no Median daily | Adopted |
| | 11 | 207-208 | Reference Section 2.3 which describes constraints. Also, could you use the drum gages | | Interesting concept. For this paper we avoided |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| | | | to discharge warm surface water out of the reservoir in the summer and potentially cool the reservoir in the fall? Has this been looked into? | | speculating about operational changes and focus on current constraints. Future studies may warrant modification to operations, although in the example you suggest we would then be just shifting the high temperature releases into summer to potential aid fall. At this time the concern we hear more about is summer temperature issues in the lower river. |
| | 13 | 214-216 | Are these the only available outlets at Grand Coulee Dam? | | Yes – there are two levels of functioning regulating outlets. Both are described. |
| | 14 | 232 | What about heat gain from solar inputs? | | The RT influences the relative influence of the advective influence. So with lower RT the net gain of energy from solar radiation on the reservoir should be more influential. |
| | 14 | | General comment: Consider a conclusion that ties Section 2.2.3.1 back to water temperatures. | | Added a summary sentence to the section. |
| | 18 | 313 | Consider adding a conclusion. Where is the so what statement(s)? | | Added a sentence in the summary paragraph to |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| | | | | | high-light that Grand Coulee released the coolest water possible during the 2015 sockeye migration season. |
| | 22 | 344 | Section 2.3: Either put in the front, or tie operational constraints more to water temperature discussion | | We've gone back and forth on order of the operations/temperature issue. We decided to put temperature at the front because that is the focus of this paper, but added language to try and tie the constraints to the temperature discussion. |
| | 24 | 386-400 | Move section under Section 2.3.3?? | | Adopted |
| | 34 | 581 | There is some thermal stratification in the summer, however there is no cold water reserves like that found in Dworshak Res. | | Included |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| Berger | 8, Table 2-2 | 140 | Formatting error in last row | | Corrected |
| Berger | 10 | 176-179 | Suggest breaking sentence into 2 sentences. Also, “Data” is plural | “Presumable fall and winter temperatures are very similar from below Grand Coulee Dam to below Priest Rapids Dam near Pasco, Washington (upstream of the confluence with the Snake River). Data are limited at Pasco, Washington in the fall and winter.” | Adopted |
| Berger | 10 | 182-185 | Suggest breaking sentence into 2 sentences. | “The last few days in August into September the temperatures in Lake Roosevelt are at their annual peak, and atmospheric conditions are such that water actual cools as it travels downstream. This condition likely holds until the reservoir becomes more isothermal in October (as described in the next section).” | Adopted |
| Berger | 10, Table 2-3 caption | 189 | “Data” is plural | “at Spalding, ID data are for comparison…” | Adopted |
| Berger | 12, Figure 2-5 | | It would be helpful to show penstock elevations in this figure. | | Good suggestion, included. |
| Berger | 15 | 263 | Format error, “Figure 2-9” referenced twice | | Fixed |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| Berger | 16 | 272-275 | Suggest breaking sentence into 2 sentences. | "In 2015, Grand Coulee outflows during June and early July were 1 to 2 degrees cooler than Columbia River temperatures upstream at the international boundary (Figure 2-10). This is a pattern that occurs each year where Grand Coulee Dam releases water that is cooler than inflows during spring and summer and warmer during fall and winter. | Adopted |
| Berger | 18 | 311 | edit | "as it moves downstream **in** the Middle-Columbia reach," | Adopted |
| Berger | 18, Table 2-5 | | Text quality in table is low.  Also table extends beyond margins. | Re-insert table into document | Fixed |
| Berger | 30 | 543 | The longer residence time of Dworshak could also be listed in the bullets | | Added |
| Berger | 36 | 602 | A space is needed between "Figure 5-1" and "is" | | Adopted |
| Wells | | 41 | "Grand Coulee Dam has no potential to mitigate for downstream temperatures". The words "no potential" are probably not correct. I think that we could probably explore many pathways to affect temperatures downstream but they would impact power production and Banks Lake. So I think it is safer to say "limited" rather than "no" potential. | Change this to "has limited potential to mitigate for downstream temperatures". | Adopted |
| Wells | 10 | | Fig 2.4 – nice figure – it says a lot! | None | Thank you. |

| Reviewer | Pg | Line | Comment | Suggested Revision | Comment Resolution |
|---|---|---|---|---|---|
| Wells | 13 | 230 | “The RT controls the significance of the advective source of heat, with shorter RT corresponding to increased influence of advective heat gain.” During cooling periods this would affect not heat gain, but heat loss. | “The RT controls the significance of the advective source of heat, with shorter RT corresponding to increased influence of advective heat gain or loss.” | Adopted |
| Wells | 32,33 | | Fig 2-20 and 2-21 appear to be duplicates | Eliminate one of the figures. | Fixed |
| Wells | 34 | 576 | “to develop thermal stratification behind the dam” | “to develop thermal stratification.” | Adopted |
| Wells | 34 | 583 | “No additional potential exists…” | “Little additional potential exists…” | Adopted |