

# RECLAMATION

*Managing Water in the West*

## Thermal Regime of the Columbia River at Lake Roosevelt



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

June 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.

# 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



# Table of Contents

## Acronyms and Abbreviations

## Executive Summary

<b>1</b>	<b>Introduction.....</b>	<b>3</b>
<b>2</b>	<b>Lake Roosevelt and Grand Coulee Dam.....</b>	<b>4</b>
2.1	Setting and Project Description .....	4
2.2	Temperature Regimes and Stratification .....	7
2.2.1	Temperatures above and below Grand Coulee .....	7
2.2.2	Reservoir Stratification .....	10
2.2.3	Reservoir Retention Time .....	13
2.2.4	Conditions in 2015.....	14
2.3	Grand Coulee Current Operations and Constraints .....	23
2.3.1	Fall Operations .....	25
2.3.2	Winter Operations.....	26
2.3.3	Spring Operations.....	27
2.3.4	Summer Operations .....	28
2.3.5	Summary of Dworshak Dam Operations and Water Temperature.....	28
<b>3</b>	<b>Conclusion .....</b>	<b>32</b>
<b>4</b>	<b>References .....</b>	<b>33</b>
<b>5</b>	<b>Appendix A: Grand Coulee Dam and Franklin D. Roosevelt Reservoir Thermal Stratification .....</b>	<b>35</b>

## List of Tables

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.....	7
Table 2-2.	Columbia River and Lake Roosevelt temperature sources. ....	8
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 .....	10
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. ....	12
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). ....	15

## List of Figures

Figure 2-1.	Overview diagram of Grand Coulee Dam and key features. ....	5
Figure 2-2.	Location of Grand Coulee Dam on the Columbia River. ....	6
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. ....	8
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. ....	9
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. ....	11
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. ....	12
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 20 <sup>th</sup> - and 80 <sup>th</sup> -percentile values. ....	14
Figure 2-8.	Grand Coulee Dam outflows for water year 2015 vs. 30-year average. ....	15
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). ....	16
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). ....	18
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. ....	19

Figure 2-12. Columbia River temperatures downstream of Priest Rapids Dam, near Pasco, WA. ....	19
Figure 2-13. Snake River temperatures downstream of Lower Granite Dam. ....	20
Figure 2-14. Columbia River temperatures downstream of The Dalles Dam.....	21
Figure 2-15. Salmon River temperatures at Whitebird, Idaho. ....	22
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.....	23
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. ....	24
Figure 2-18. Monthly average residence time of Lake Roosevelt and Dworshak Reservoir in terms of the ratio between storage volume and flow rate $f$ or the 2000-2015 (2003-2015 for Dworshak) water years. ....	30
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 18°C.....	30
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 18°C.....	31
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).....	31
Figure 5-1. Thermal stratification figures to demonstrate how to read figures in this appendix.....	36
Figure 5-2. Lake Roosevelt thermal stratification for water year 2016.....	37
Figure 5-3. Lake Roosevelt thermal stratification for water year 2015.....	37
Figure 5-4. Lake Roosevelt thermal stratification for water year 2014.....	38
Figure 5-5. Lake Roosevelt thermal stratification for water year 2013.....	38
Figure 5-6. Lake Roosevelt thermal stratification for water year 2012.....	39
Figure 5-7. Lake Roosevelt thermal stratification for water year 2011.....	39
Figure 5-8. Lake Roosevelt thermal stratification for water year 2010.....	40
Figure 5-9. Lake Roosevelt thermal stratification for water year 2009.....	40
Figure 5-10. Lake Roosevelt thermal stratification for water year 2006.....	41
Figure 5-11. Lake Roosevelt thermal stratification for water year 2007.....	41
Figure 5-12. Lake Roosevelt thermal stratification for water year 2006.....	42
Figure 5-13. Lake Roosevelt thermal stratification for water year 2005.....	42
Figure 5-14. Lake Roosevelt thermal stratification for water year 2004.....	43

Figure 5-15. Lake Roosevelt thermal stratification for water year 2003.....	43
Figure 5-16. Lake Roosevelt thermal stratification for water year 2002.....	44
Figure 5-17. Lake Roosevelt thermal stratification for water year 2001.....	44
Figure 5-18. Lake Roosevelt thermal stratification for water year 2000.....	45
Figure 5-19. Temperatures dating from 2015 to 2013 at the approximate forebay elevations of the intakes for the Left and Right Power Plants. ....	46
Figure 5-20. Temperatures dating from 2012 to 2010 at the approximate forebay elevations of the intakes for the Left and Right Power Plants. ....	47
Figure 5-21. Temperatures dating from 2009 to 2007 at the approximate forebay elevations of the intakes for the Left and Right Power Plants. ....	48
Figure 5-22. Temperatures dating from 2006 to 2004 at the approximate forebay elevations of the intakes for the Left and Right Power Plants. ....	49
Figure 5-23. Temperatures dating from 2003 to 2001 at the approximate forebay elevations of the intakes for the Left and Right Power Plants. ....	50
Figure 5-24. Temperatures in 2000 at the approximate forebay elevations of the i ntakes for the Left and Right Power Plants.....	51



# 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 is 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<sup>1</sup> 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.

---

<sup>1</sup> 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).

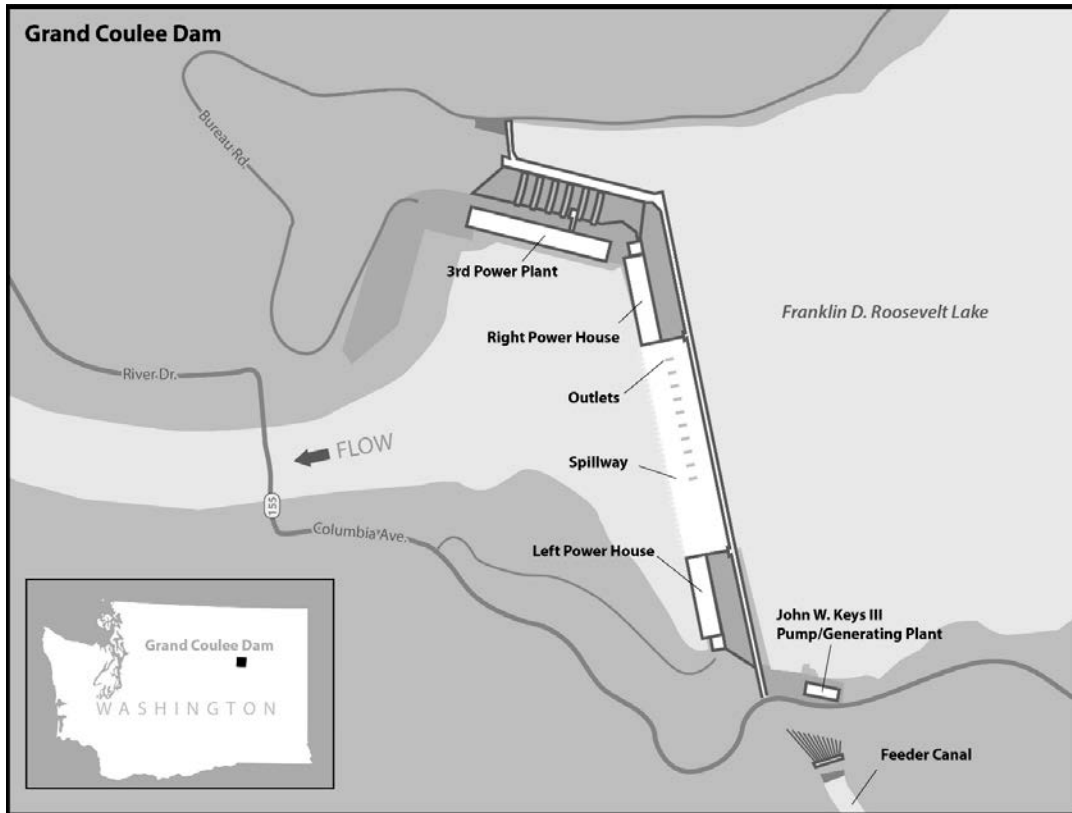


Figure 2-1. Overview diagram of Grand Coulee Dam and key features.



**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) <sup>a</sup>	Approximate Total Powerplant Capacity (MW) <sup>a</sup>
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
<sup>a</sup> 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<sup>2</sup> (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.

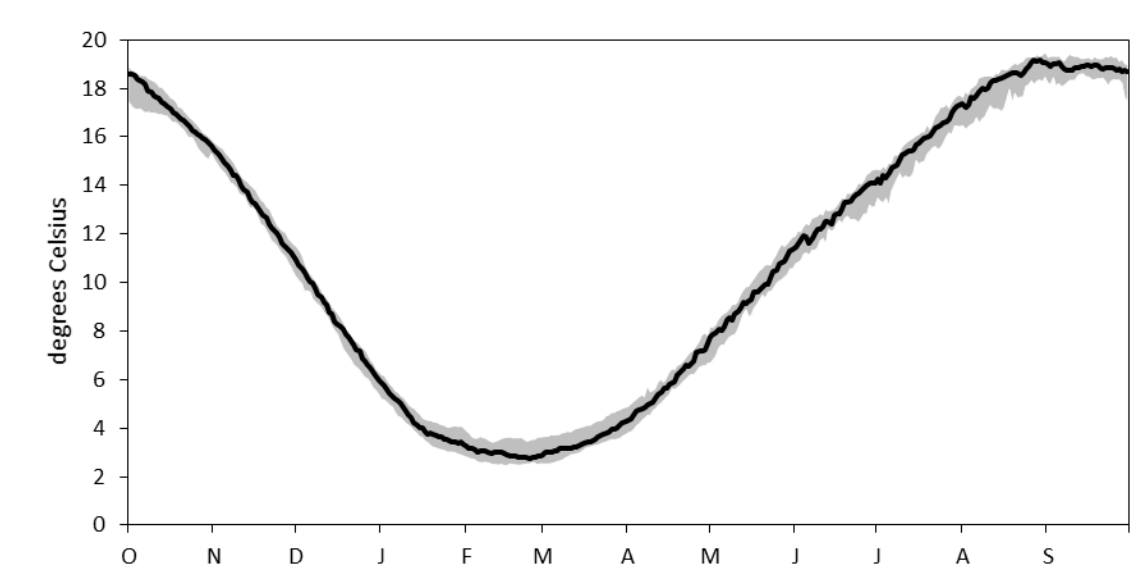
---

<sup>2</sup> <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

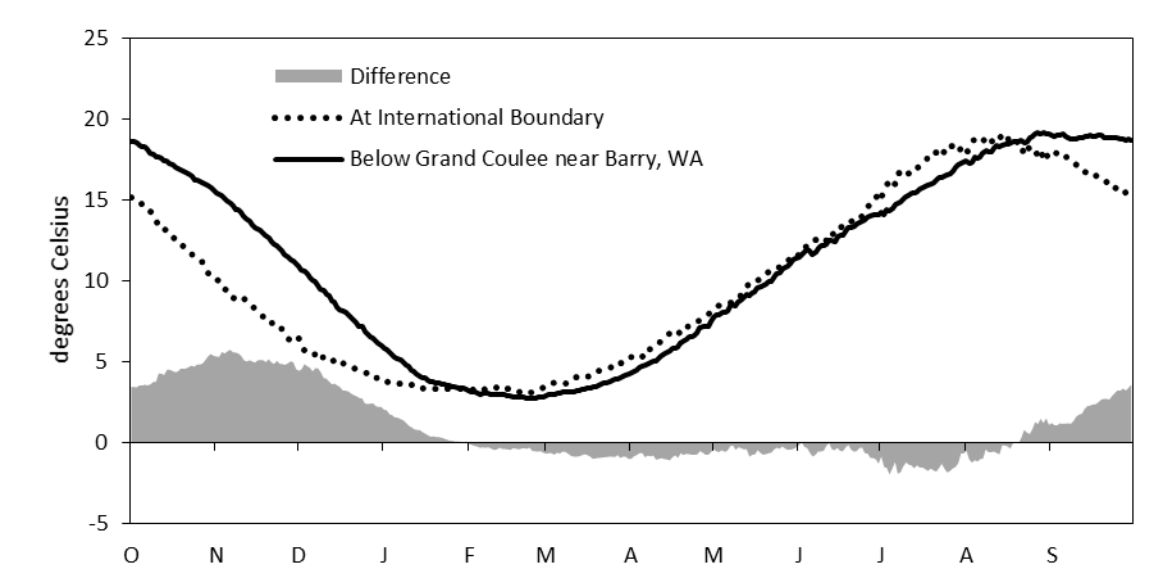
Median temperatures below Grand Coulee Dam generally range from a low of about 3 degrees Celsius (°C) during the winter to a high of about 19°C by the end of summer (Figure 2-3).



**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
<b>Columbia River at International Boundary</b>	13	8	5	3	3	4	7	10	13	17	18	16
<b>Columbia River nr Barry, WA</b>	17	13	8	4	3	4	6	9	13	16	18	19
<b>Columbia River at Pasco, WA</b>	17	na	na	na	na	5	8	12	15	18	20	19
<b>Clearwater River at Spalding, ID</b>	11	7	4	3	4	6	7	9	12	13	12	13

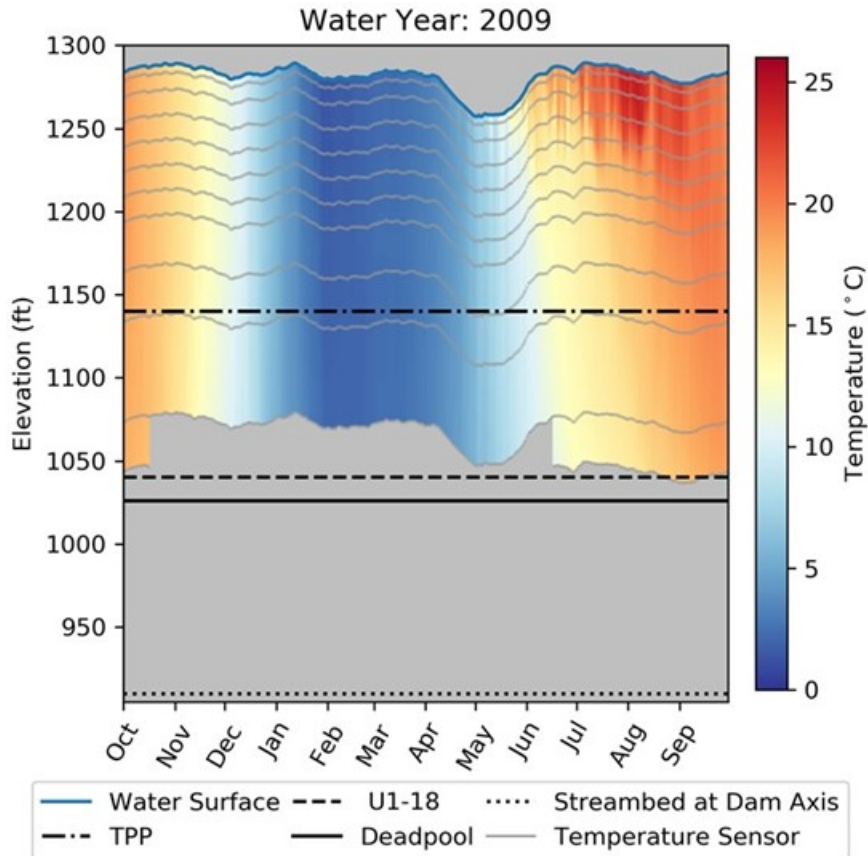
Downstream of Grand Coulee Dam the Columbia River flows through Lake Rufus Woods, the reservoir behind the USACE' Chief Joseph Dam; and then flows through five run-of-river PUD projects (Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids). Presumable fall and winter temperatures are very similar 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 2°C 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**

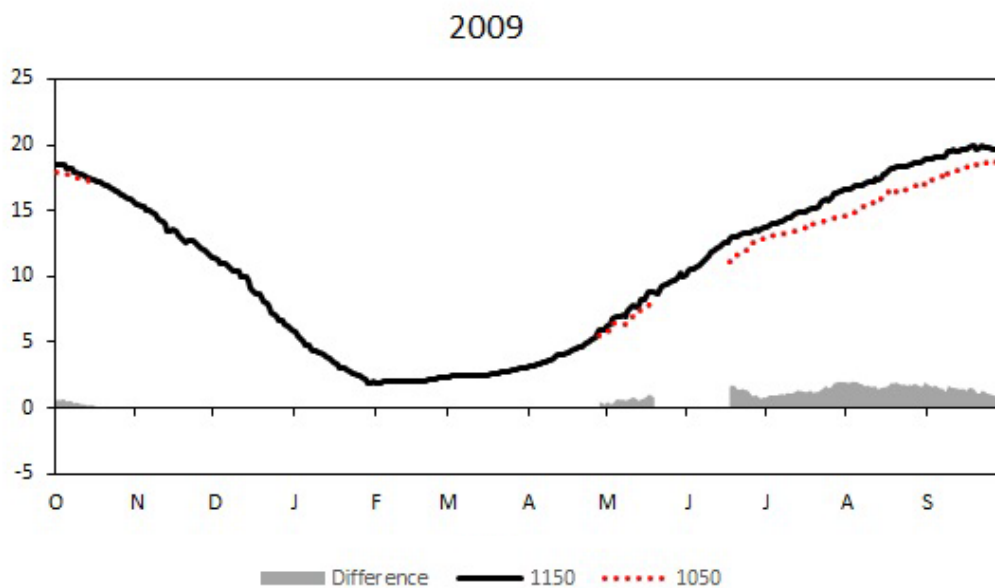
### **2.2.2.1 Lake Roosevelt**

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 2°C 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.

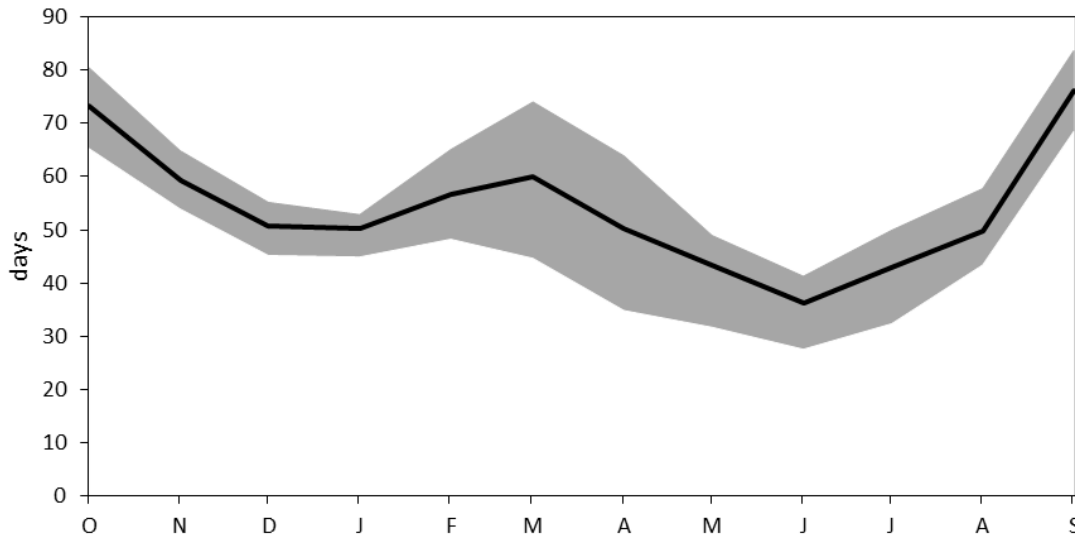
### **2.2.3.1 Grand Coulee and Lake Roosevelt**

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.



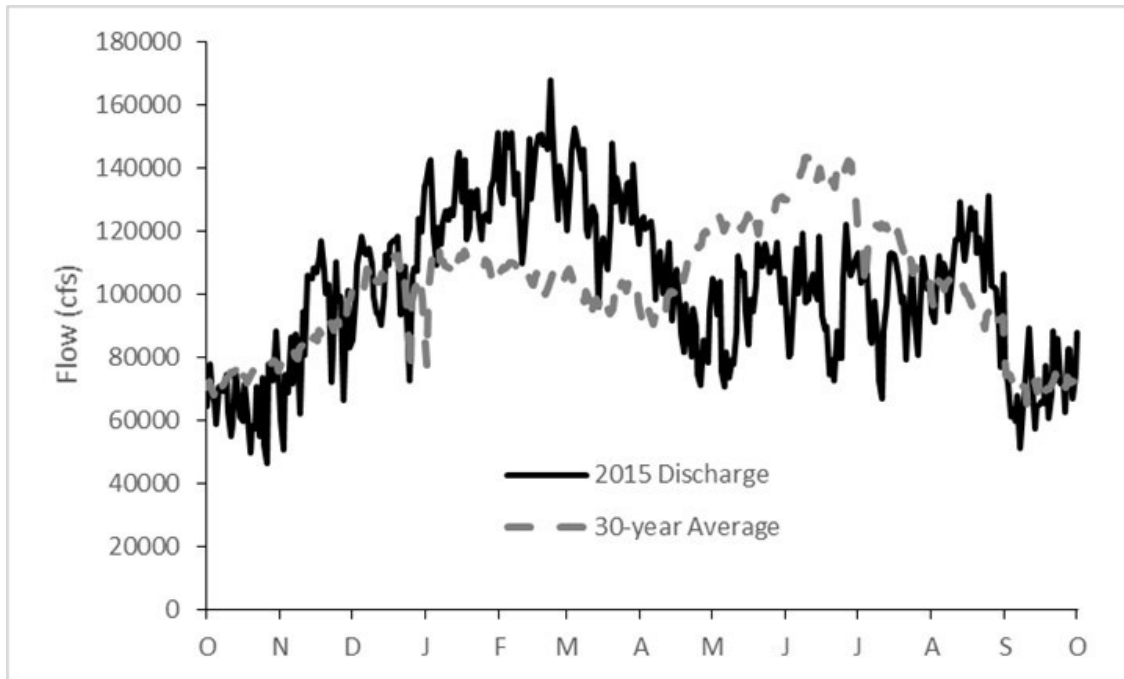
**Figure 2-7. Average monthly residence time of Lake Roosevelt presented in terms of the ratio between storage volume and flow rate for the 2000-2015 water years. Gray bounds represent the 20<sup>th</sup>- and 80<sup>th</sup>-percentile values.**

## 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).<sup>3</sup> 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-

<sup>3</sup> Other species of salmon and steelhead typically migrate outside of this time period both as juvenile and adults and were not substantially impacted.

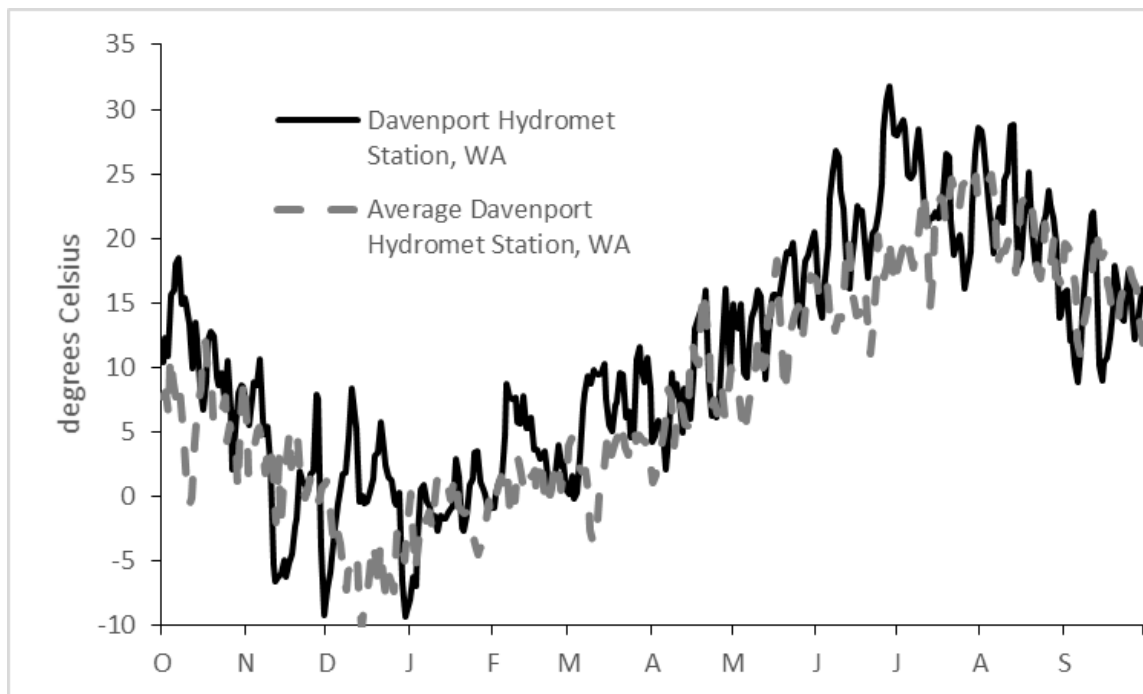
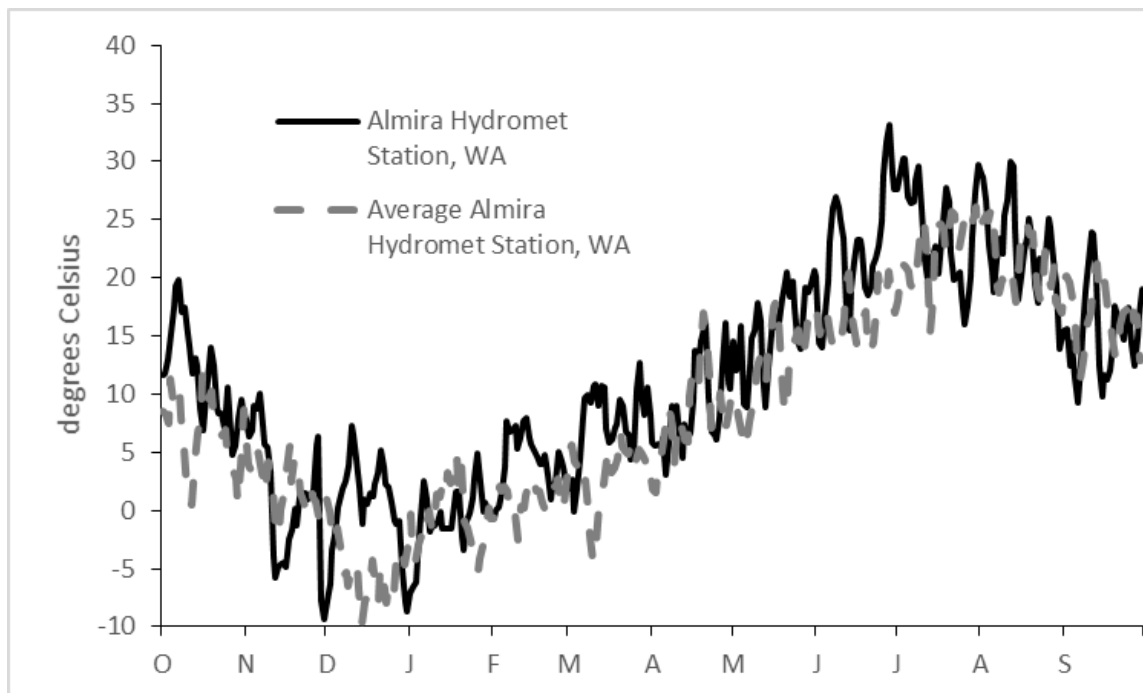
August) was well below the 30-year average at 42 MAF or 74 percent of average. The lower Columbia River and Snake River runoff volumes were even lower in comparison to the 30-year average at 67 percent (58 MAF) and 54 percent (11.5 MAF), respectively.



**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
S 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



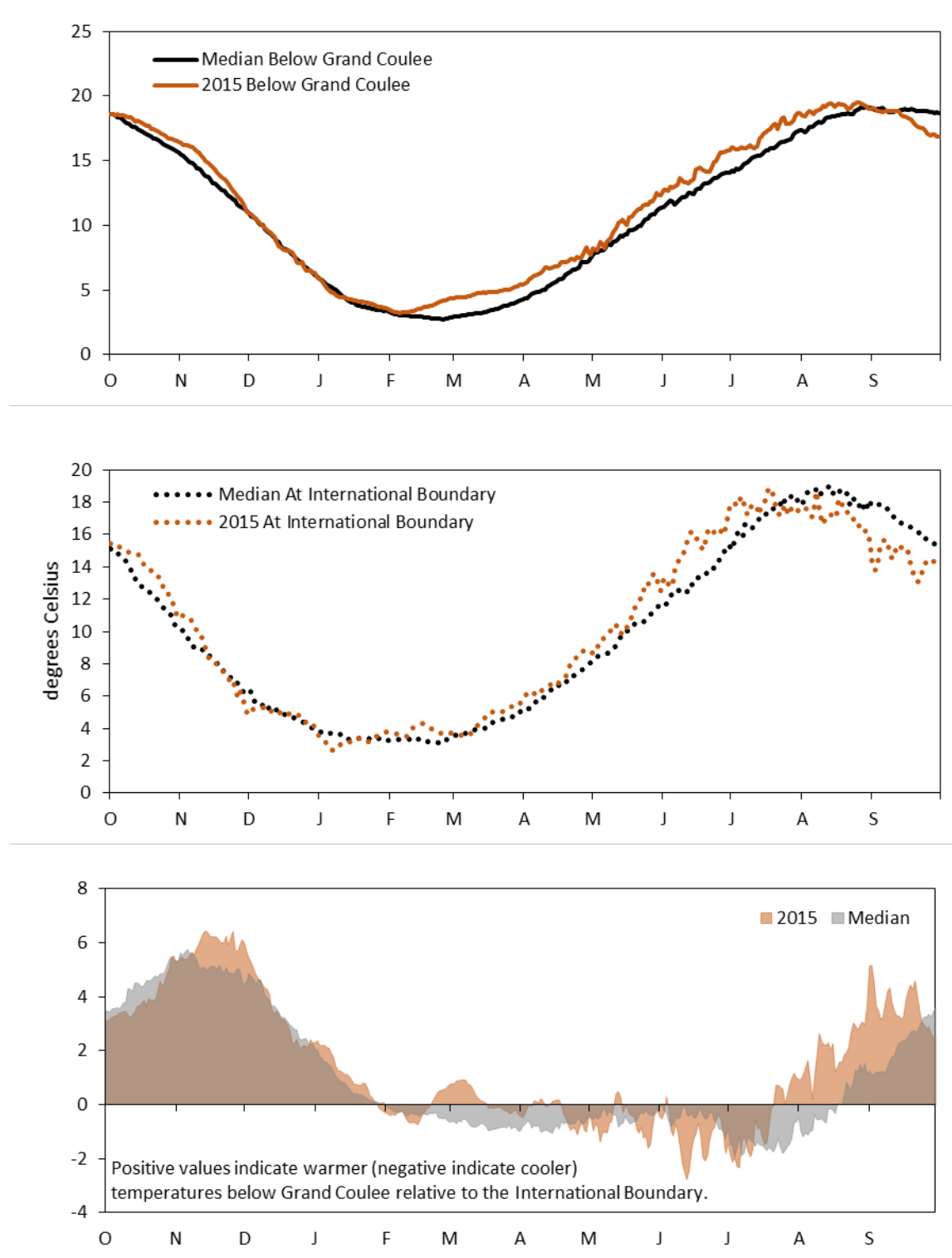
**Figure 2-9. Air temperatures at select Hydromet stations (Almira – top, Davenport – bottom) in Washington to characterize weather conditions during the 2015 water year (solid black line) compared to average conditions (dashed grey line).**



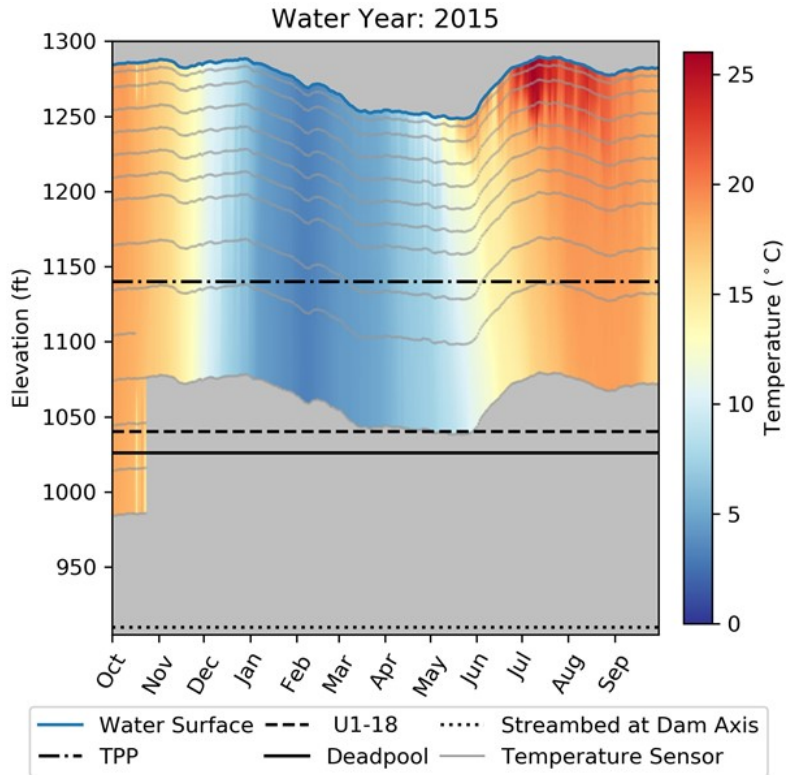
In 2015, Grand Coulee outflows during June and early July were 1 to 2°C cooler than Columbia River temperatures upstream at the International Boundary (Figure 2-10). This is a pattern that occurs each year where Grand Coulee Dam releases water that is cooler than inflow during spring and summer and warmer 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 19°C in 2015, on average the temperatures during this period are 11 to 17°C. 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).

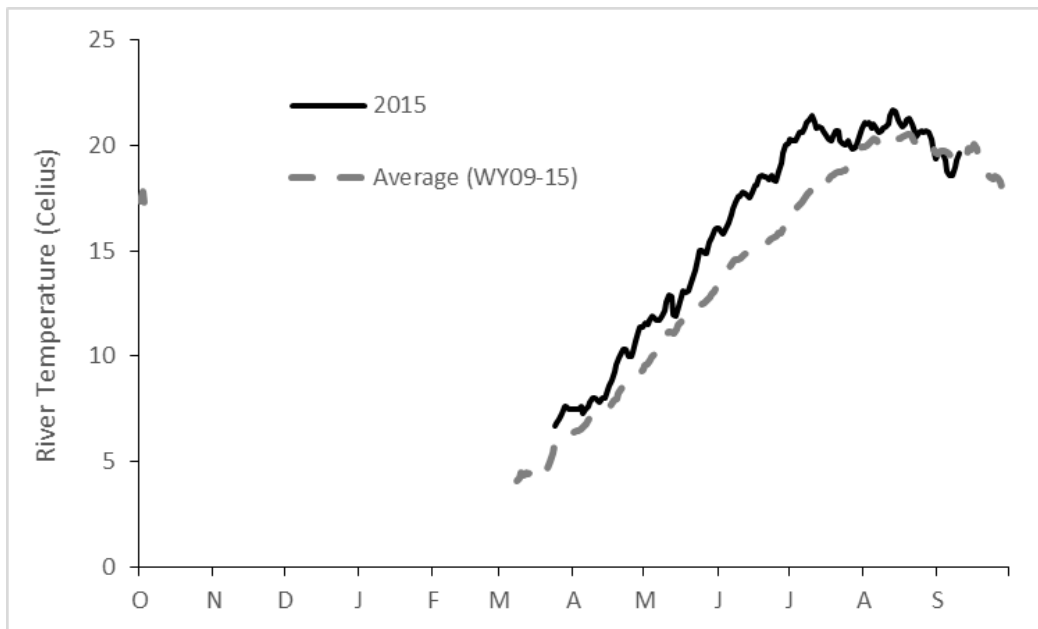
During the summer of 2015 the water temperatures increased by about 3°C such that the daily average temperatures downstream of Priest Rapids Dam (near Pasco, WA) were 16 to 21°C (average daily temperatures are typically between 14 to 20°C for this period; see Figure 2-12).



**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).**

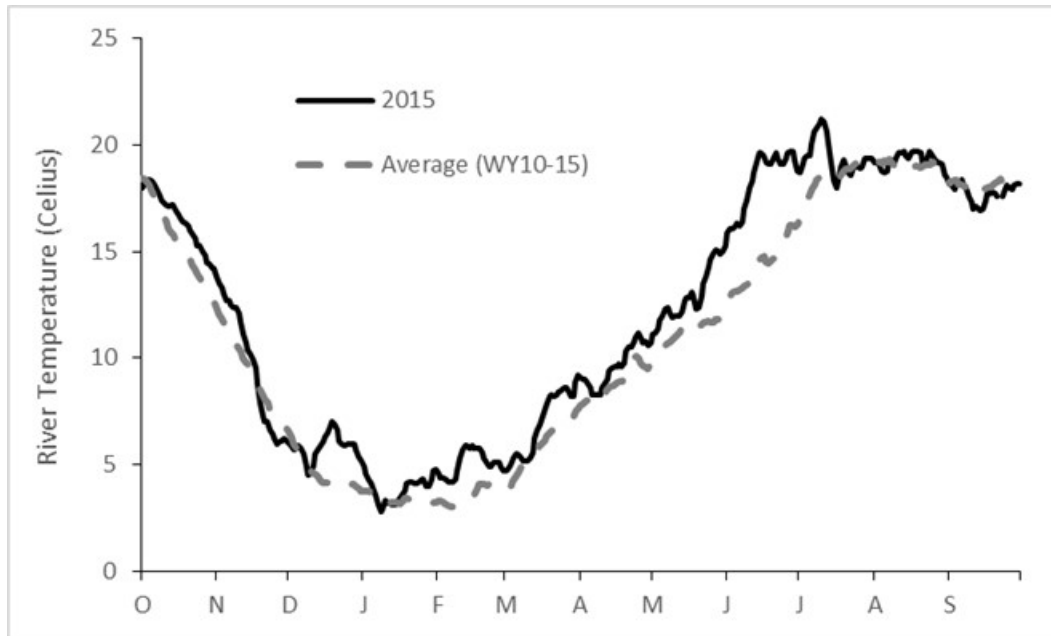


**Figure 2-11. Lake Roosevelt temperature profile for water year 2015. Grey background is missing data or above the water surface elevation. TPP is the Third Power Plant, U1-18 are the units of the Left and Right Power Plants.**

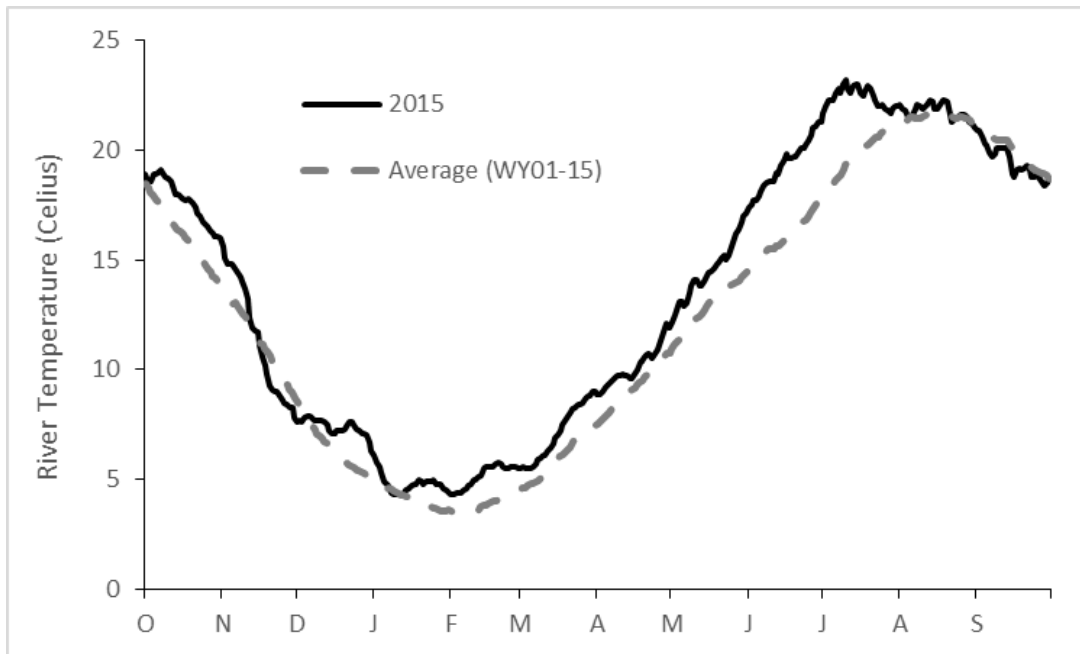


**Figure 2-12. Columbia River temperatures downstream of Priest Rapids Dam, near Pasco, WA. (Source: USGS 12514400 COLUMBIA RIVER BELOW HWY 395 BRIDGE AT PASCO, WA.)**

Daily Snake River temperatures as measured at Lower Granite Dam during the June-July period varied between 16 and 21°C (typically average daily temperatures are between 12 and 19°C 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 24°C (typically average daily temperatures are between 14 to 21°C for this period; Figure 2-14).

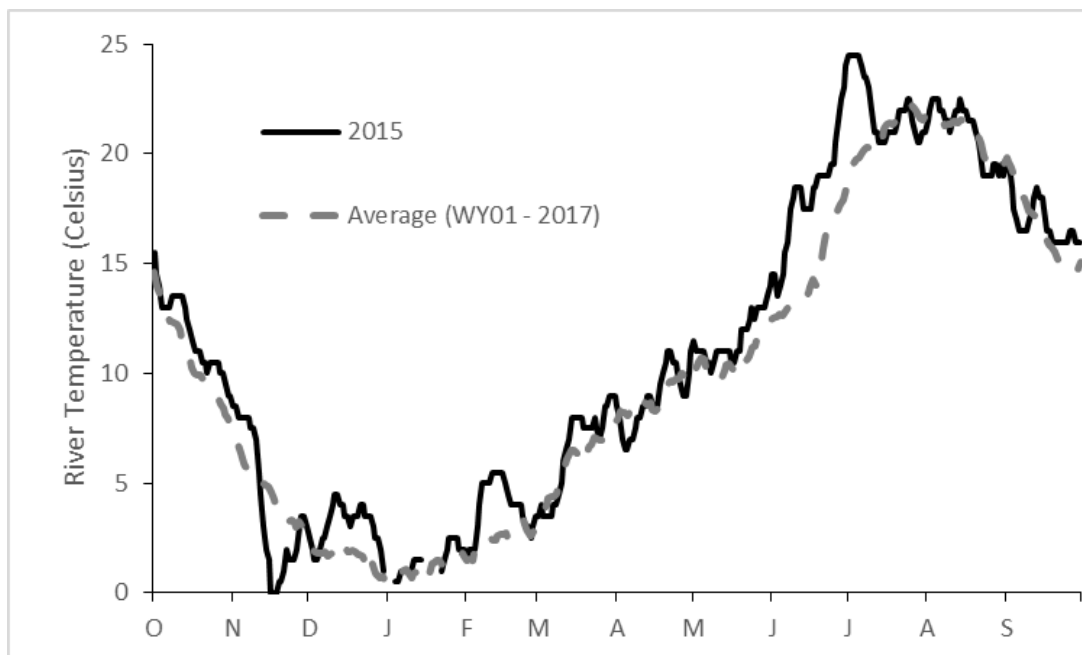


**Figure 2-13. Snake River temperatures downstream of Lower Granite Dam. (Source: USGS 13343595 SNAKE RIVER (RIGHT BANK) BL LOWER GRANITE DAM, WA.)**



**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 20°C for the month, with a maximum daily average of 24.5°C (Figure 2-15).

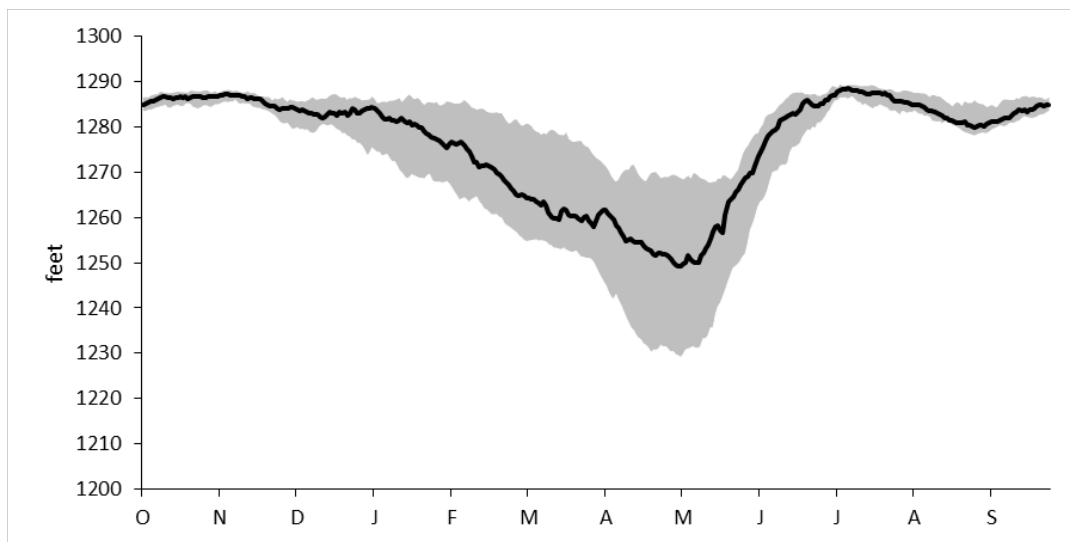


**Figure 2-15. Salmon River temperatures at Whitebird, Idaho. (Source: USGS 13317000 SALMON RIVER AT WHITE BIRD, ID.)**

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

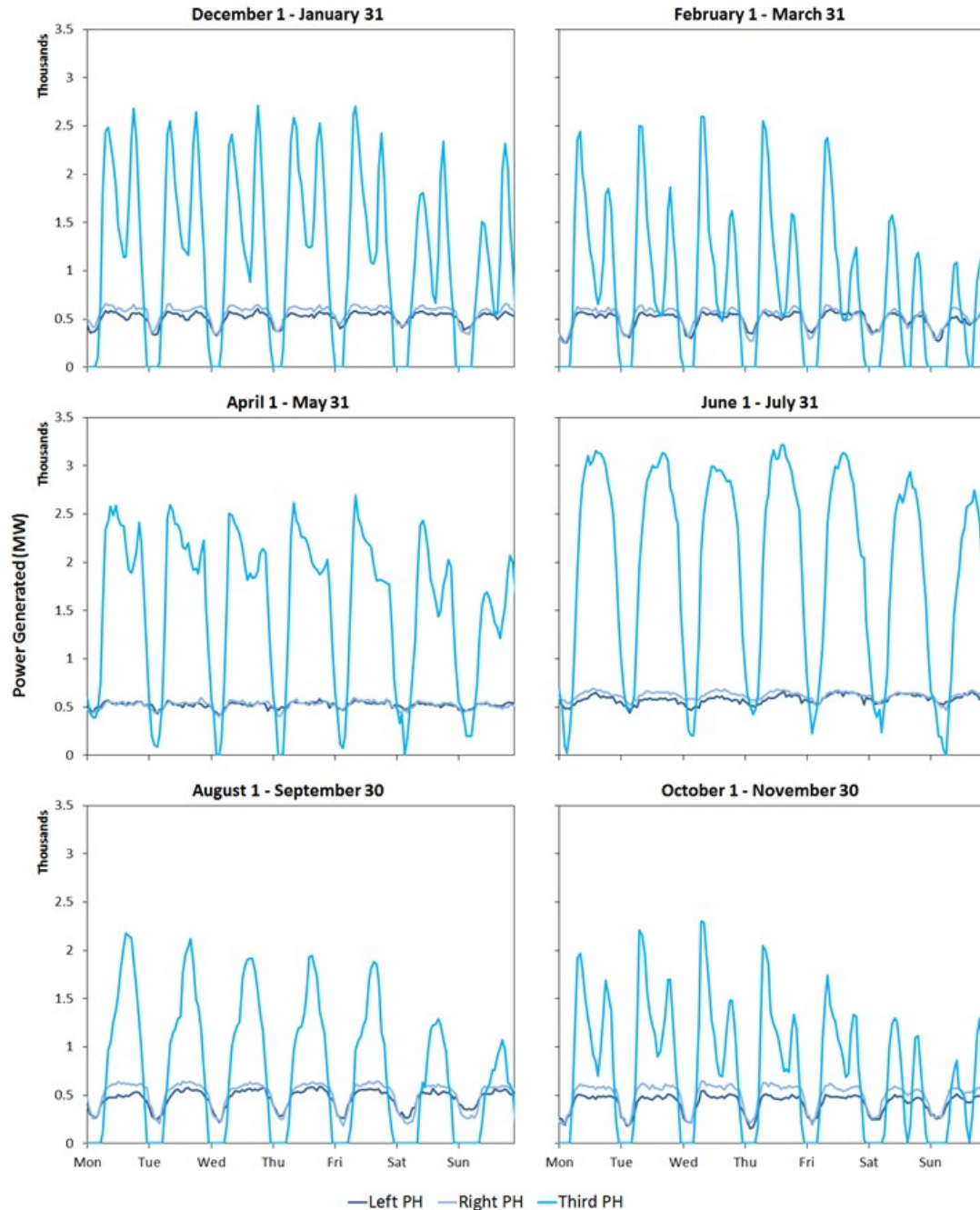
Although cold water is not available in Lake Roosevelt, it is important to recognize that Grand Coulee Dam has many operating purposes, and it is these purposes, including the configuration of the dam, that limit the ability to release theoretical cool water from the reservoir. The operations of Grand 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<sup>4</sup> 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

---

<sup>4</sup> 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<sup>5</sup> 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<sup>6</sup>, 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.<sup>7</sup> The April 10 pool elevation is intended to shape spring flows to benefit juvenile anadromous<sup>8</sup> 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

---

<sup>5</sup> Tail water is the water immediately below the dam.

<sup>6</sup> 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.

<sup>7</sup> 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).

<sup>8</sup> 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<sup>9</sup>, 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<sup>10</sup> (known as involuntary spill<sup>11</sup>). 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-

---

<sup>9</sup> A redd is the spawning nest made by fish, specifically salmon.

<sup>10</sup> Powerplant refers to the entire project, while power plant refers to an individual component, for example Third Power Plant.

<sup>11</sup> 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 support 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<sup>12</sup> 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<sup>13</sup> 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).<sup>14</sup> 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's 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

---

<sup>12</sup> Flow augmentation is a term to describe increased flow released for fish.

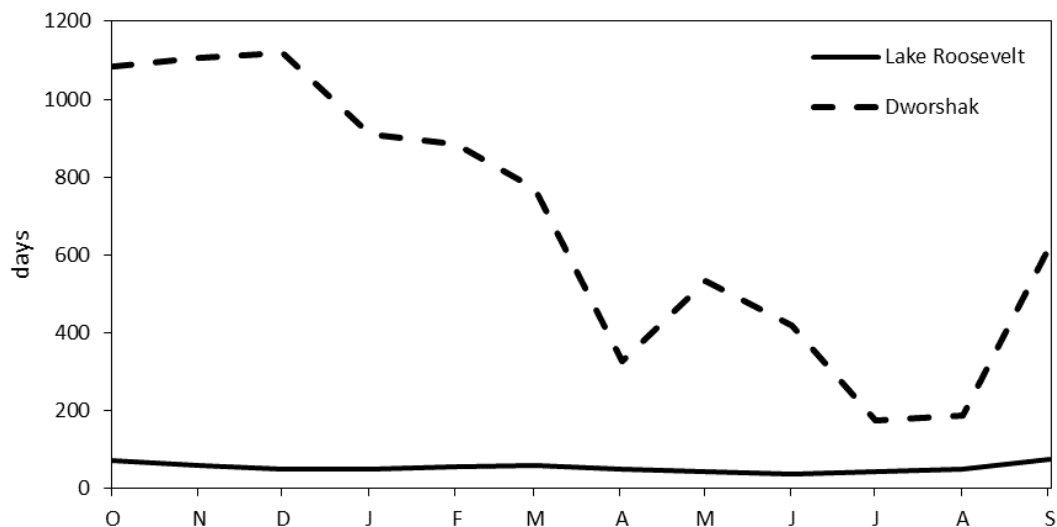
<sup>13</sup> Draft limit refers to the pool elevation that meets an operational objective.

<sup>14</sup> 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.

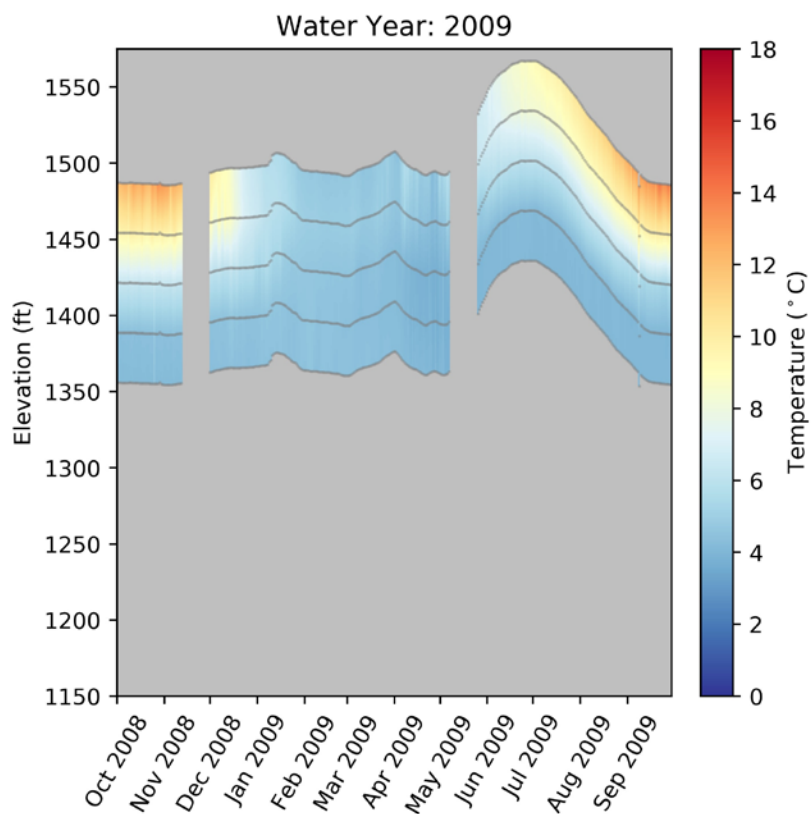
selective withdrawal of water between full pool (1,600 feet) and minimum pool (1,445 feet) elevations (USACE 2016). The purpose of the selective withdrawal is to discharge water at a temperature suitable for fish production at the downstream Dworshak National Fish Hatchery while providing cold water 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).

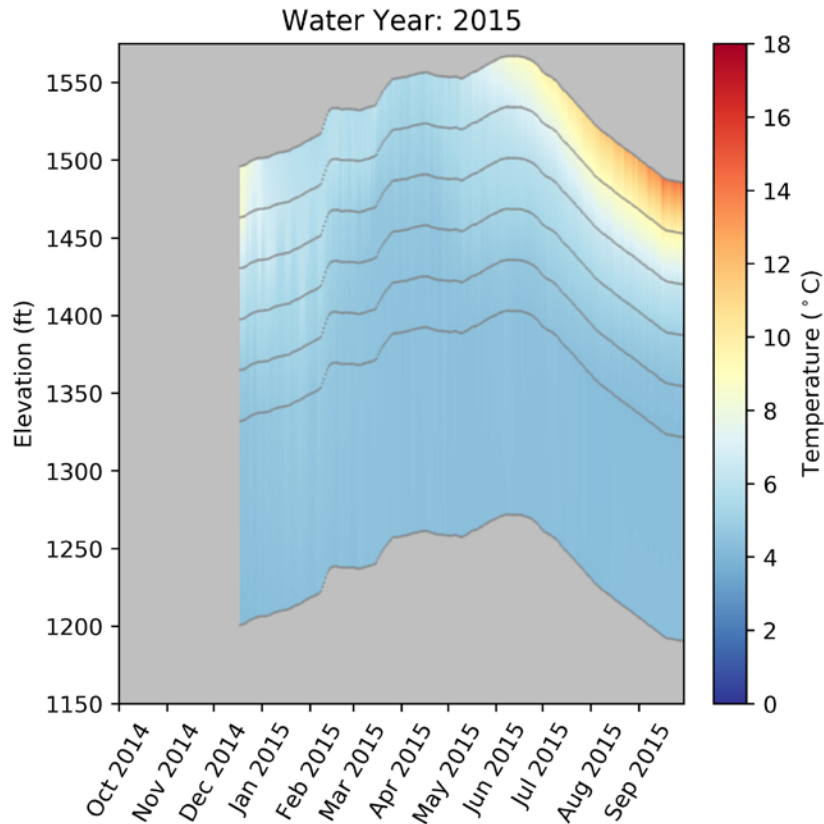
Temperature differences between the Snake River and Clearwater River at the confluence, near the upstream edge of Lower Granite Reservoir, is typically 10°C or more during July and August (Cook et al. 2006). The volume of water coming in from both the Clearwater and Snake rivers are similar in magnitude, 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).



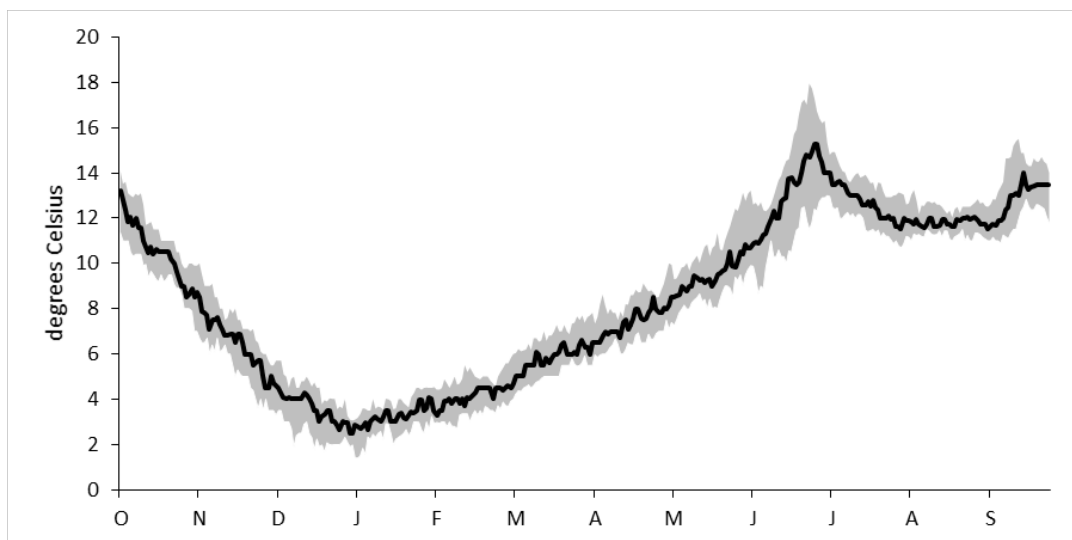
**Figure 2-18. Monthly average residence time of Lake Roosevelt and Dworshak Reservoir in terms of the ratio between storage volume and flow rate for the 2000-2015 (2003-2015 for Dworshak) water years.**



**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 18°C.**



**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 18°C.



**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<sup>15</sup> 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.

---

<sup>15</sup> 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

Parentetical Reference	Bibliographic Citation
BPA et al. 2016	Bonneville Power Administration, Bureau of Reclamation, and U.S. Army Corps of Engineers. 2016. <a href="http://www.nwd-wc.usace.army.mil/tmt/">http://www.nwd-wc.usace.army.mil/tmt/</a>
Cook et al. 2006	Cook, C., B. Dibrani, M. Richmond, M. Bleich, P. Titzler, and T. Fu. 2006. <i>Hydraulic Characteristics of the Lower Snake River during Periods of Juvenile Fall Chinook Salmon Migration, 2002-2006</i> . Final Report, Project No. 200202700, 176 electronic pages, (BPA Report DOE/BP-00000652-29).
NOAA Fisheries 2016	National Oceanic and Atmospheric Administration National Marine Fisheries Service. 2016. <i>2015 Adult Sockeye Salmon Passage Report</i> . Prepared by NMFS West Region, Portland, Oregon.
NWRFC 2016	National Weather Service, Northwest River Forecast Center. 2015. Northwest River Forecast Center. [ONLINE] Available at: <a href="https://www.nwrfc.noaa.gov/rfc/">https://www.nwrfc.noaa.gov/rfc/</a> . [Accessed 14 September 2016].
Straškraba 1999	Straškraba, S.M. 1999. <i>Retention Time as a Key Variable of Reservoir Limnology. Theoretical Reservoir Ecology and its Application</i> , 385-410. International Institute of Ecology, Brazilian Academy of Sciences and Backhuys Publishers.
USACE 2016	U.S. Army Corps of Engineers. 2016. <a href="http://www.nww.usace.army.mil/Locations/District-Locks-and-Dams/Dworshak-Dam-and-Reservoir/">http://www.nww.usace.army.mil/Locations/District-Locks-and-Dams/Dworshak-Dam-and-Reservoir/</a> . Walla Walla District. Washington.



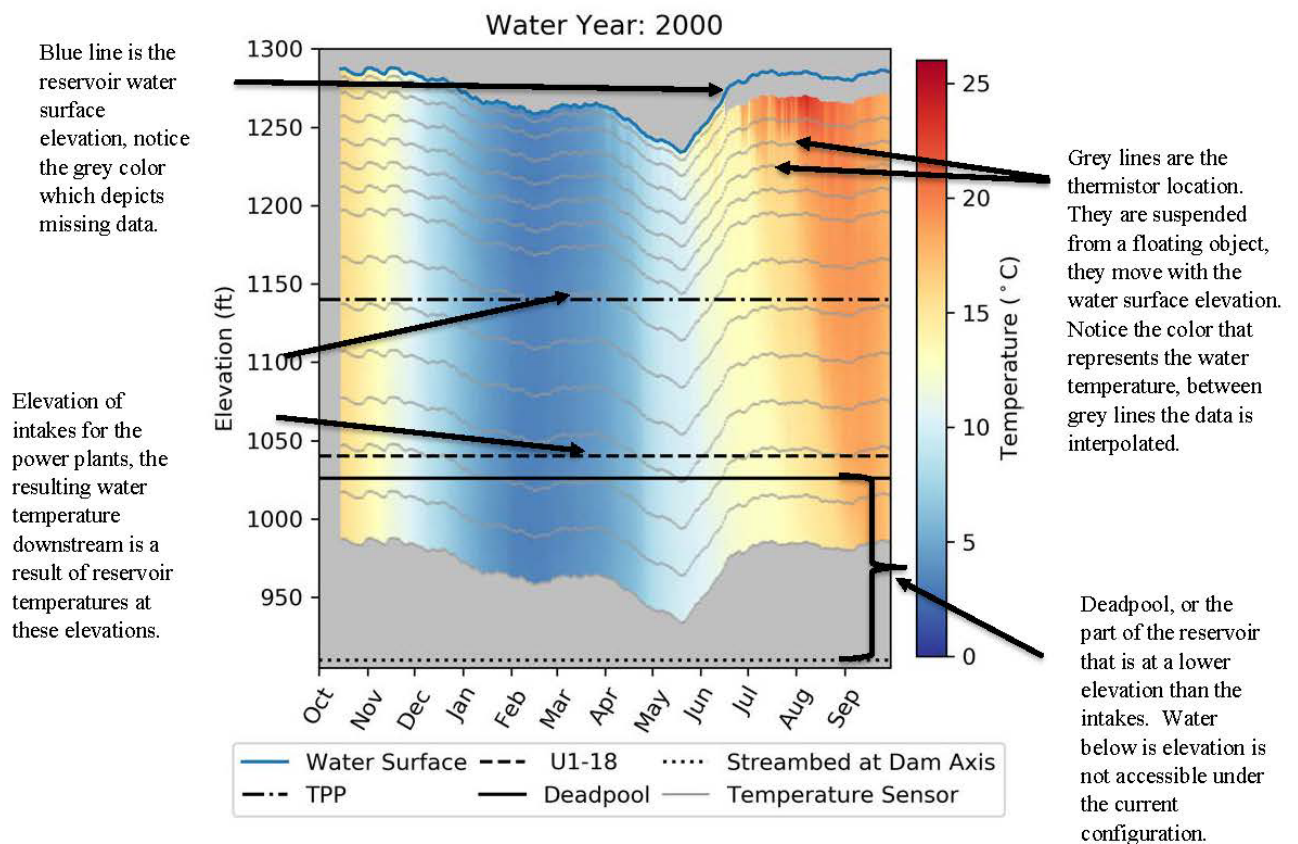
## 5 APPENDIX A: GRAND COULEE DAM AND FRANKLIN D. ROOSEVELT RESERVOIR THERMAL STRATIFICATION

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°C.

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).

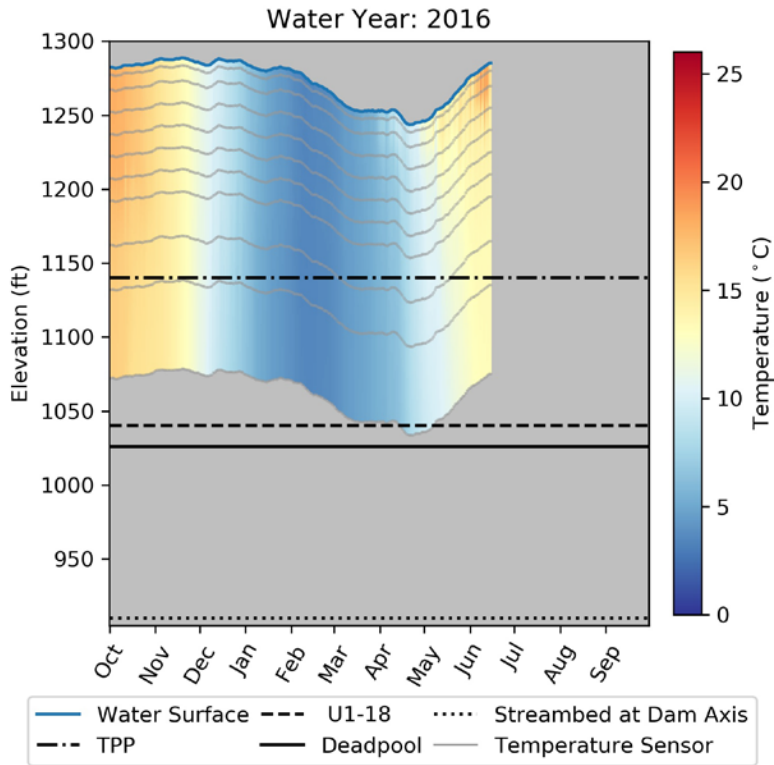
During later spring and summer, the reservoir stratifies, but most of this stratification is at or near the surface. Temperatures at the elevations of the power plant intake elevations are very similar.

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

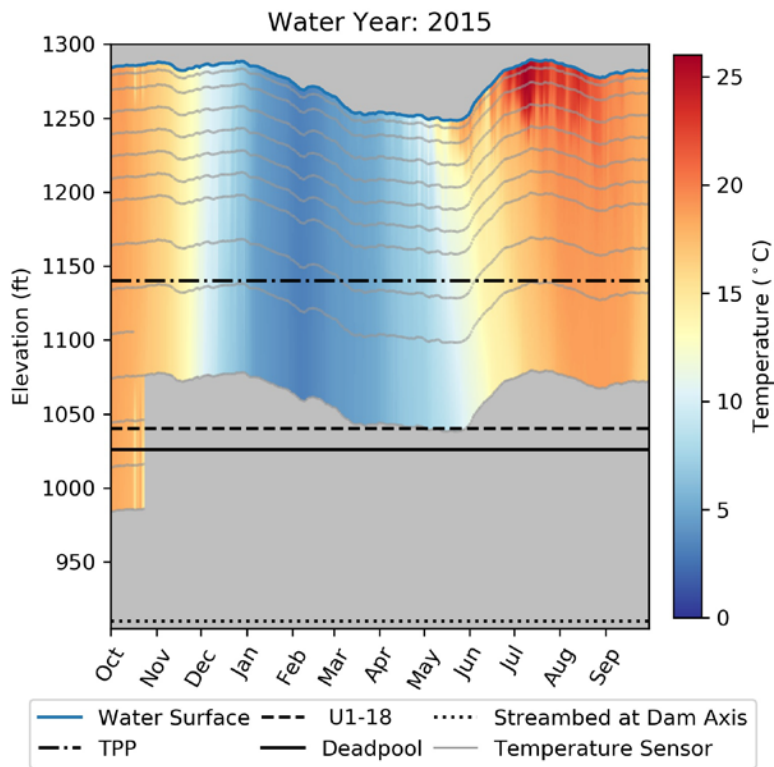


**Figure 5-1. Thermal stratification figures to demonstrate how to read figures in this appendix.**

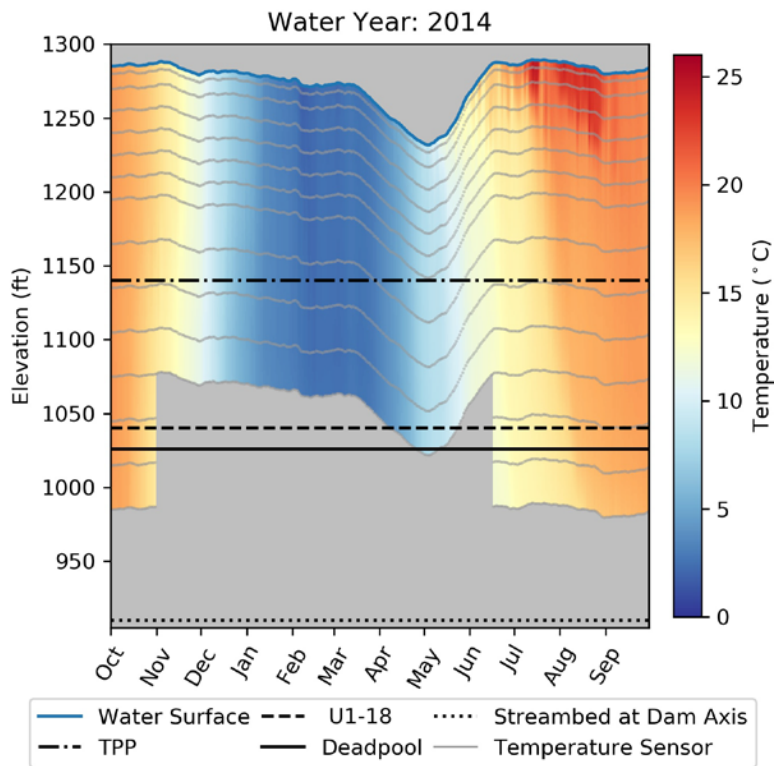
The following figures (Figure 5-2 through Figure 5-18) display the pool temperature data for Lake Roosevelt for water years dating back from 2016 to 2000, the color scale represents 0 to 25°C.



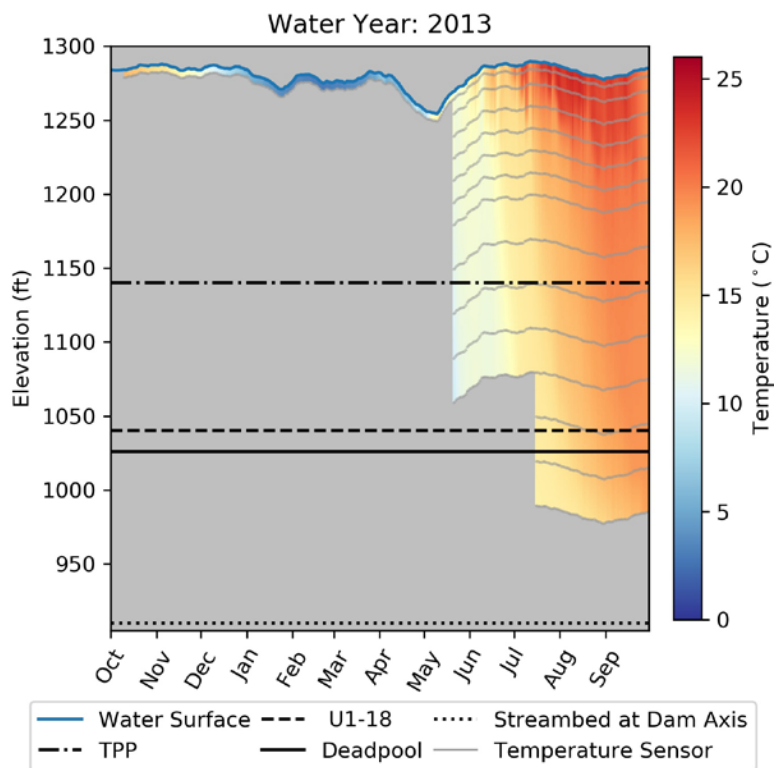
**Figure 5-2. Lake Roosevelt thermal stratification for water year 2016.**



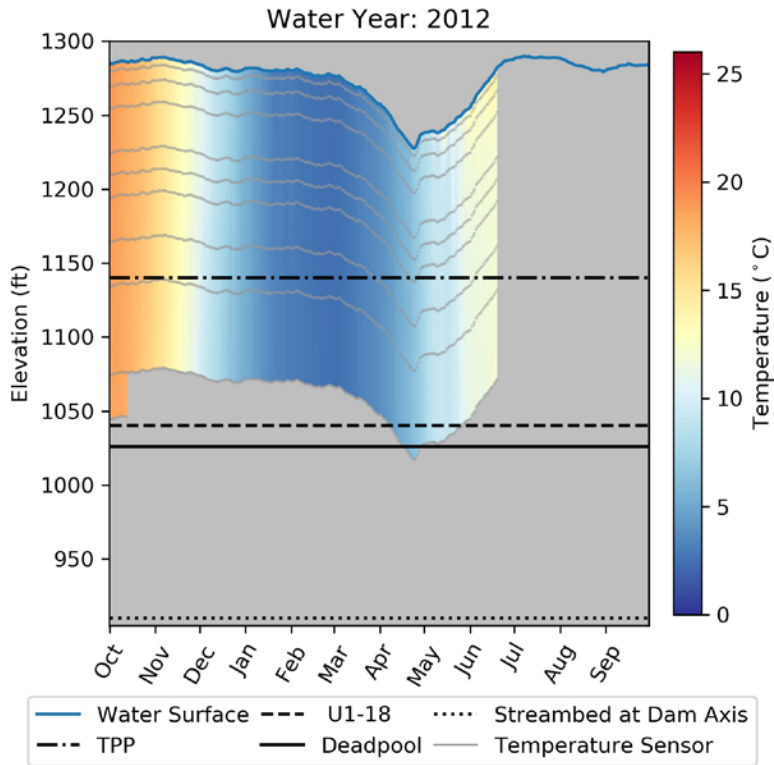
**Figure 5-3. Lake Roosevelt thermal stratification for water year 2015.**



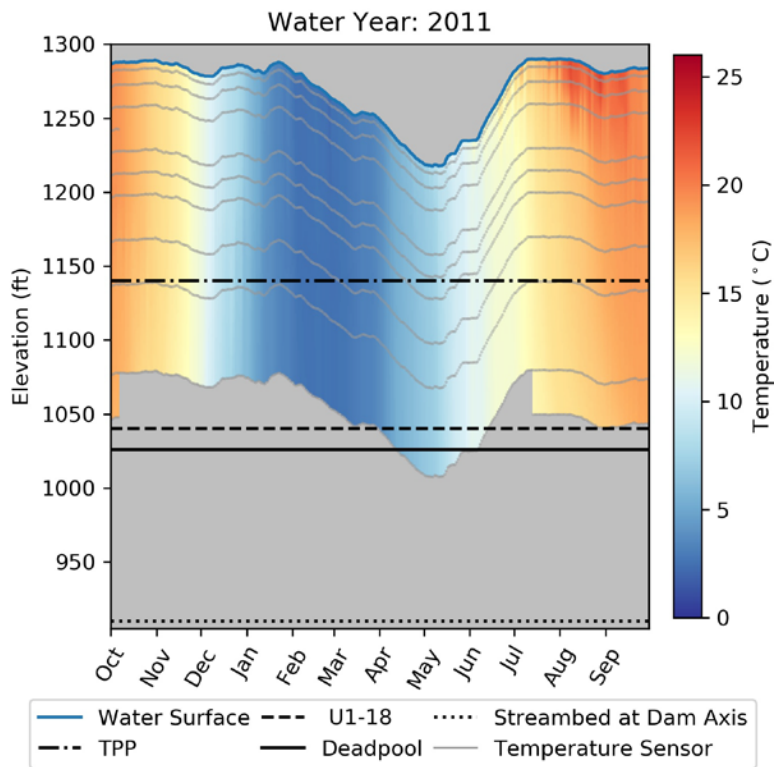
**Figure 5-4. Lake Roosevelt thermal stratification for water year 2014.**



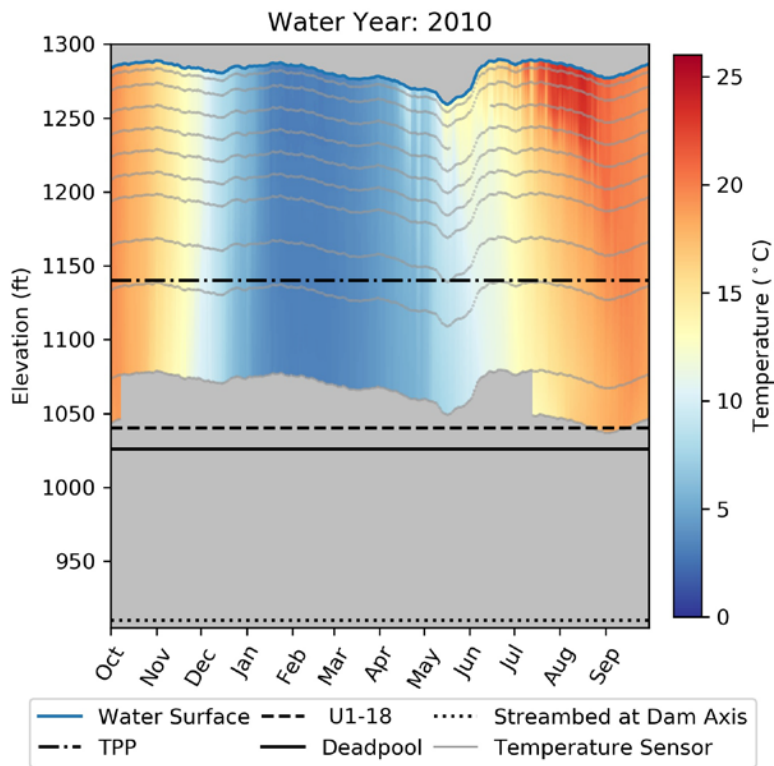
**Figure 5-5. Lake Roosevelt thermal stratification for water year 2013.**



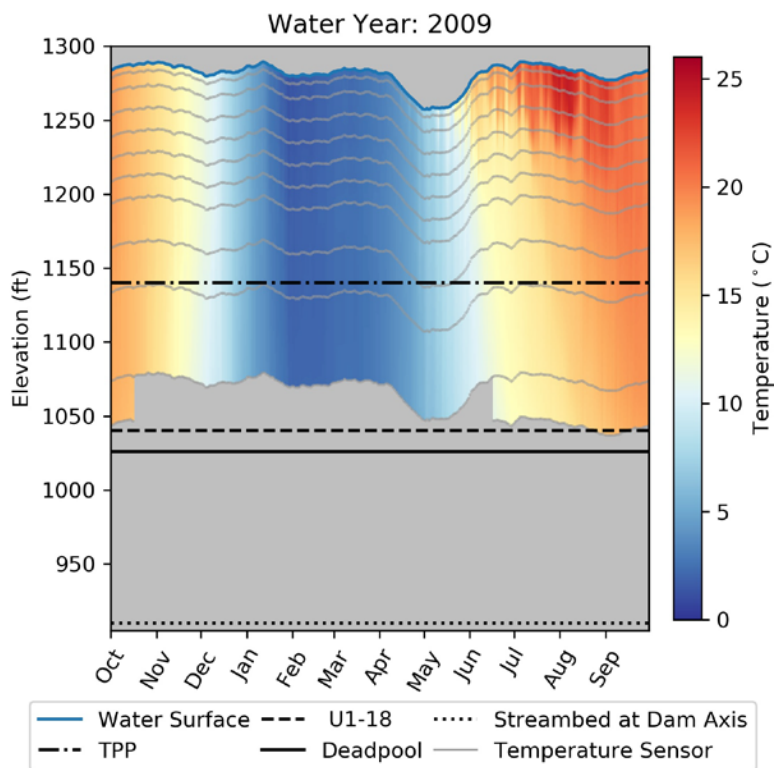
**Figure 5-6. Lake Roosevelt thermal stratification for water year 2012.**



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

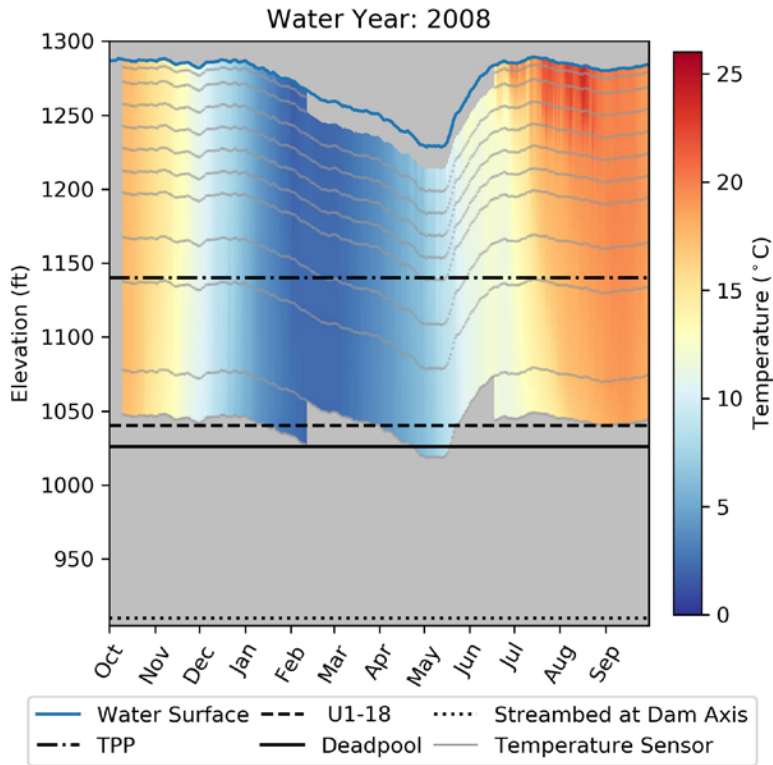


**Figure 5-8. Lake Roosevelt thermal stratification for water year 2010.**

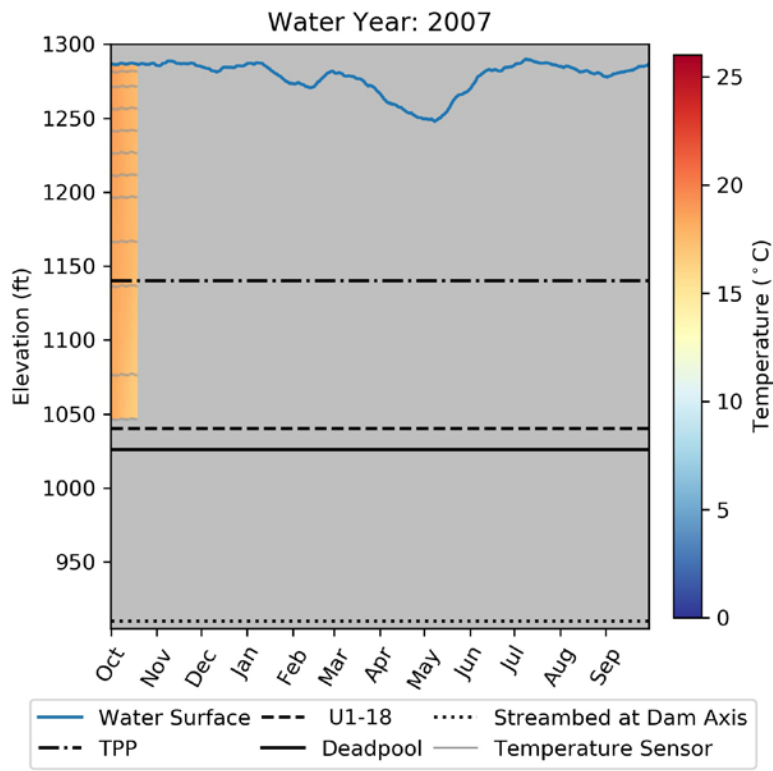


**Figure 5-9. Lake Roosevelt thermal stratification for water year 2009.**

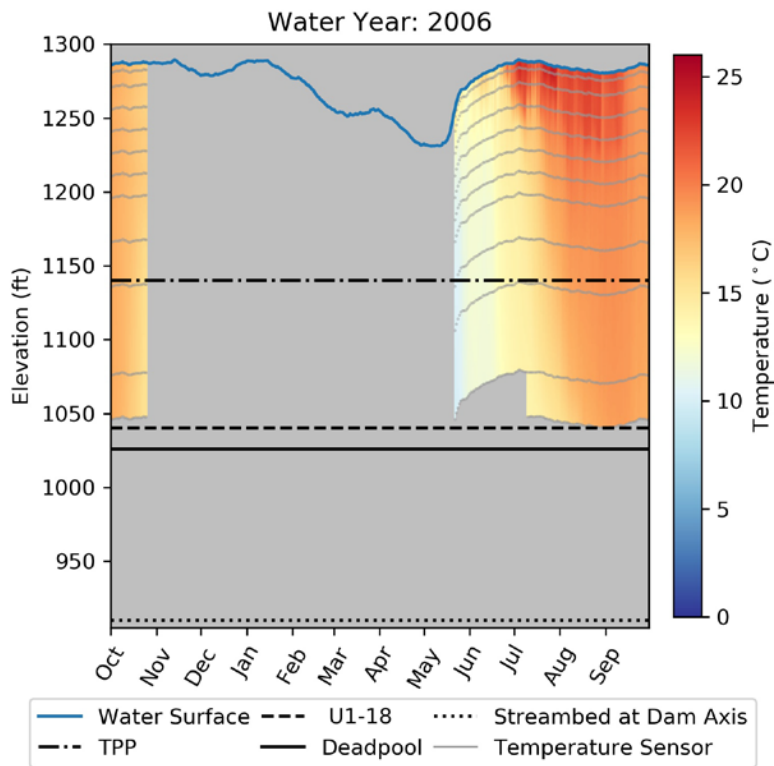




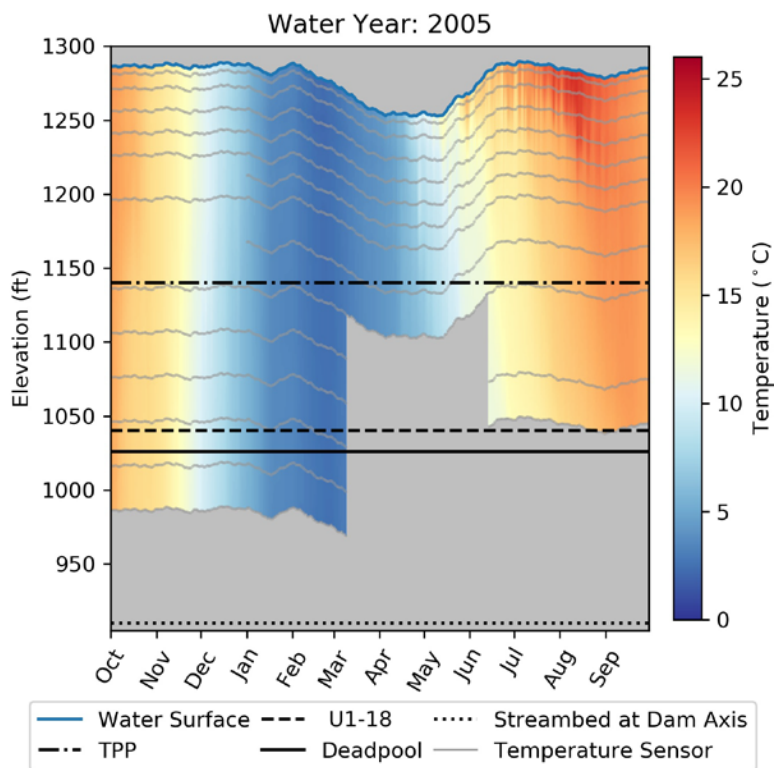
**Figure 5-10. Lake Roosevelt thermal stratification for water year 2006.**



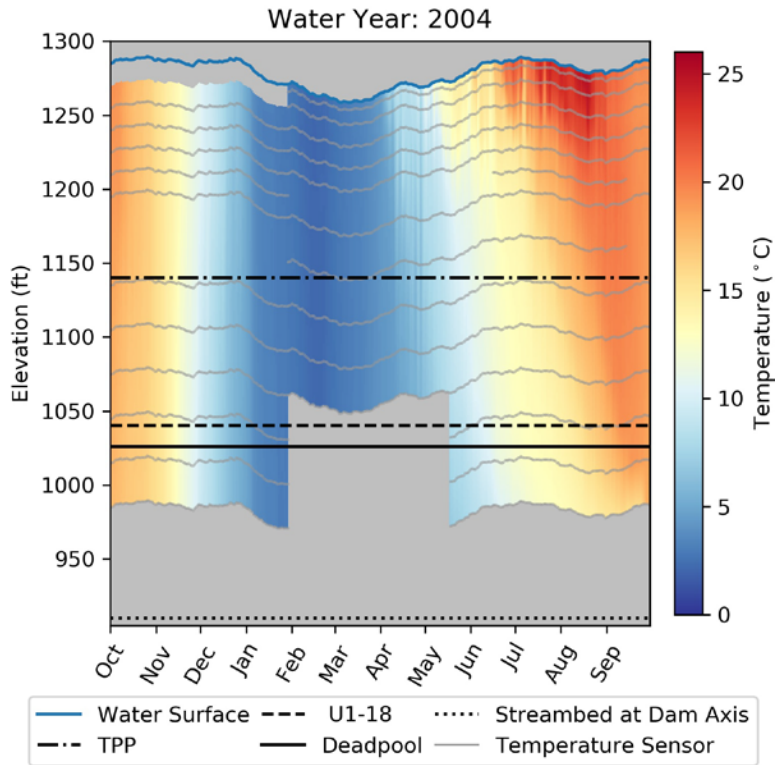
**Figure 5-11. Lake Roosevelt thermal stratification for water year 2007.**



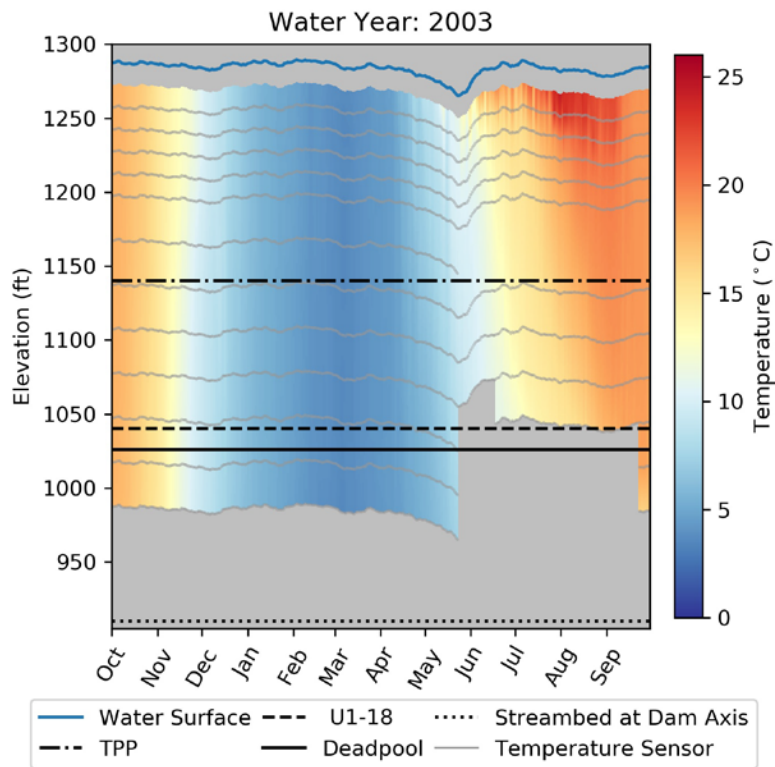
**Figure 5-12. Lake Roosevelt thermal stratification for water year 2006.**



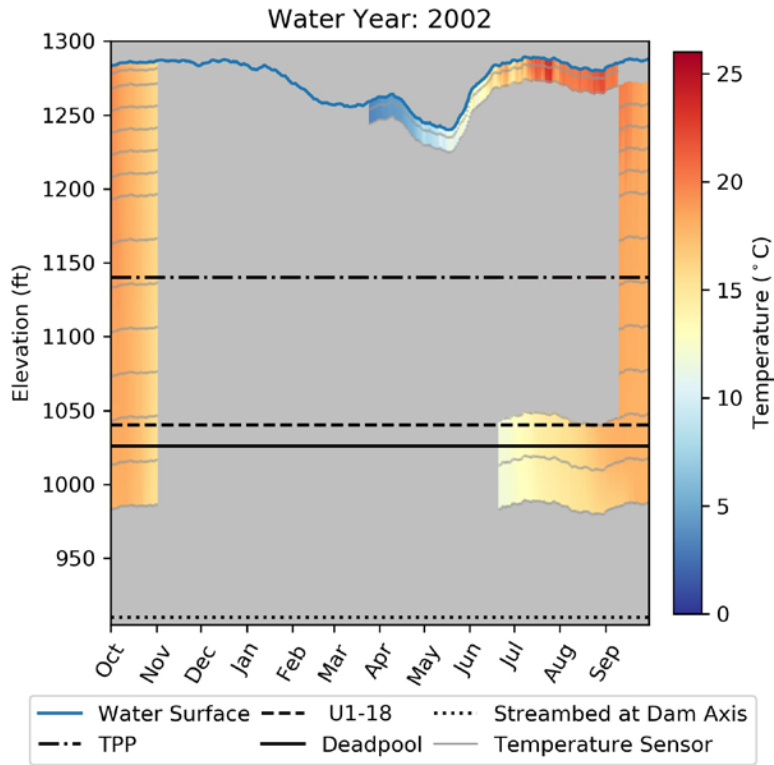
**Figure 5-13. Lake Roosevelt thermal stratification for water year 2005.**



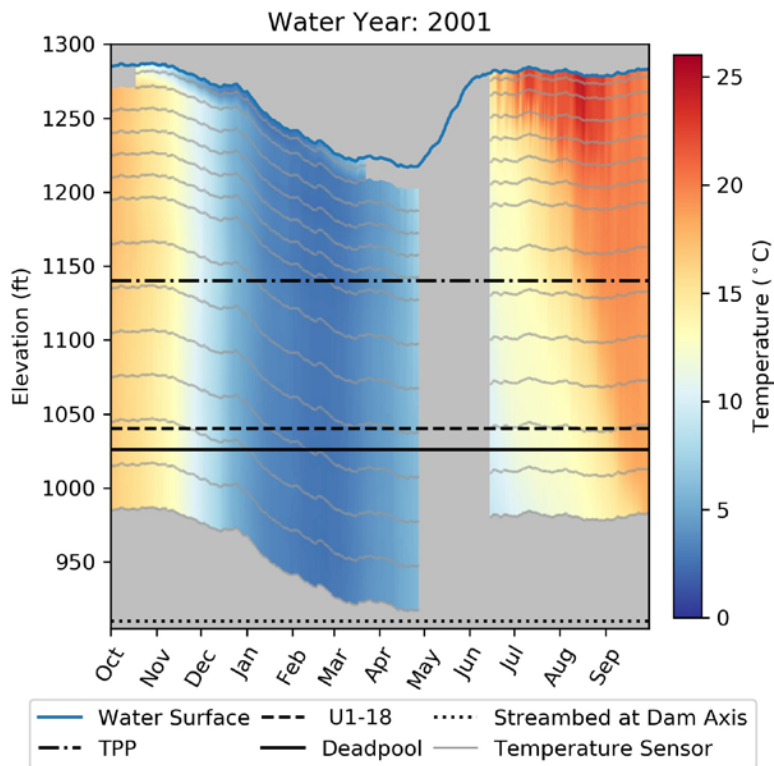
**Figure 5-14. Lake Roosevelt thermal stratification for water year 2004.**



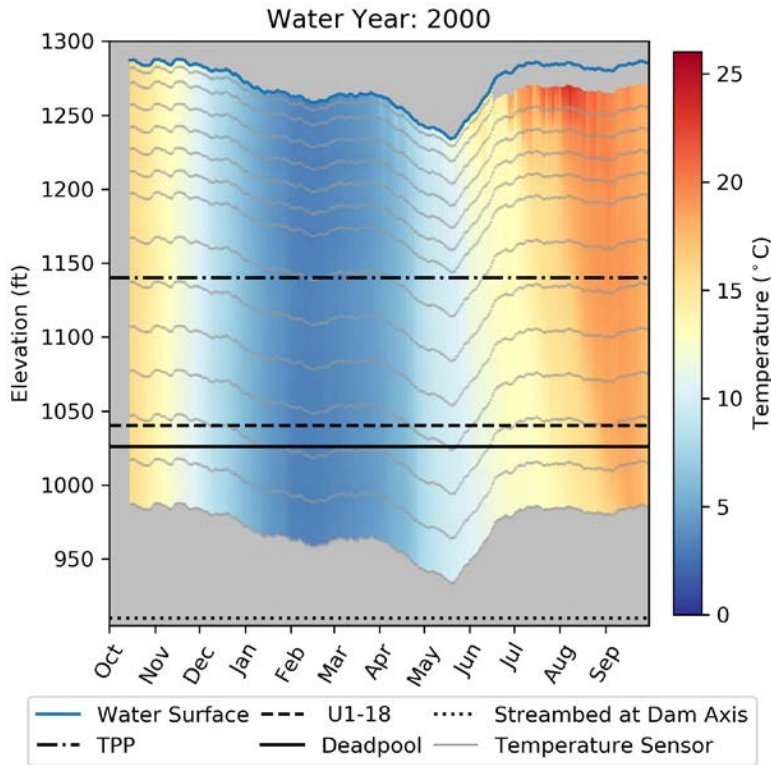
**Figure 5-15. Lake Roosevelt thermal stratification for water year 2003.**



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

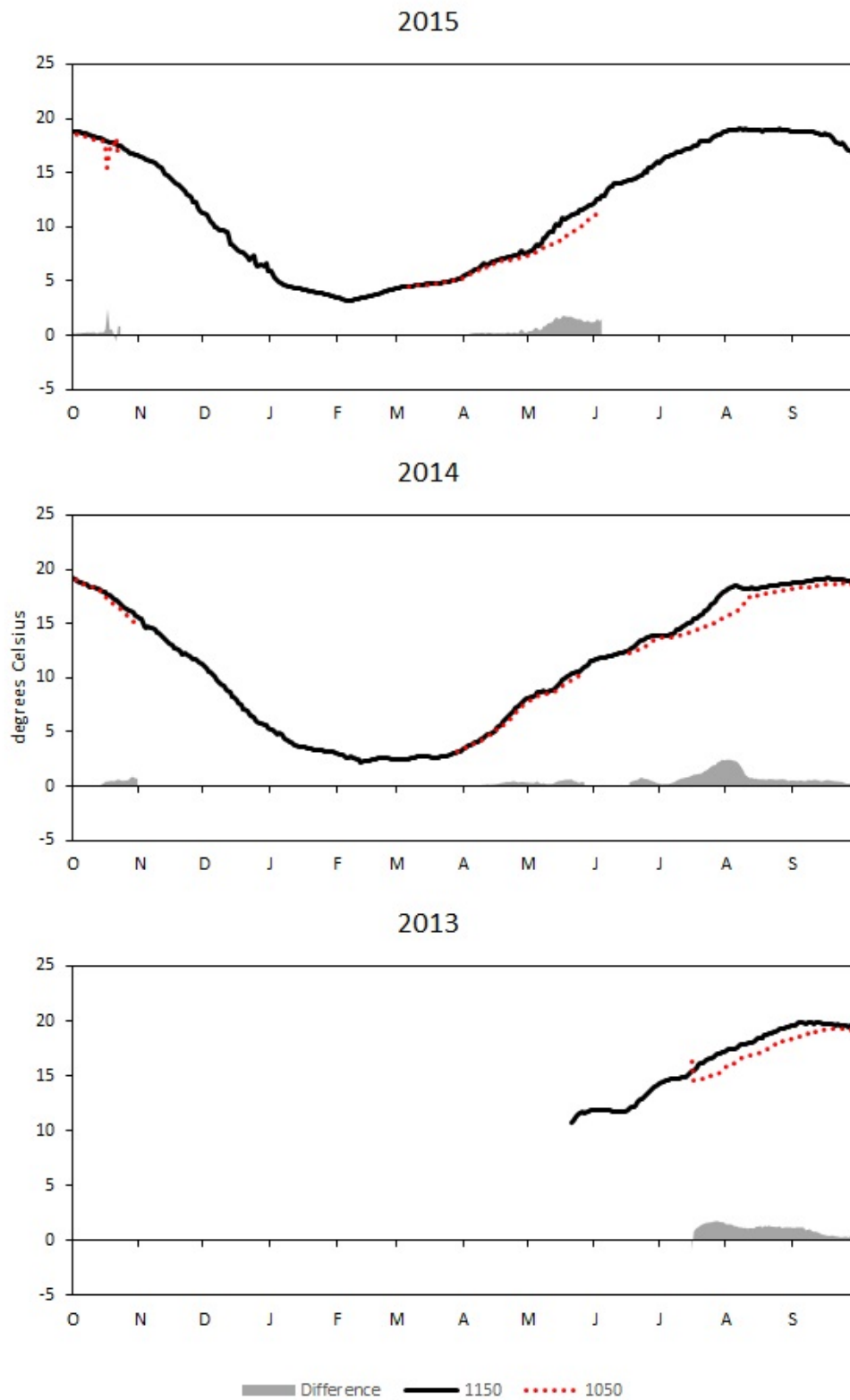


**Figure 5-17. Lake Roosevelt thermal stratification for water year 2001.**

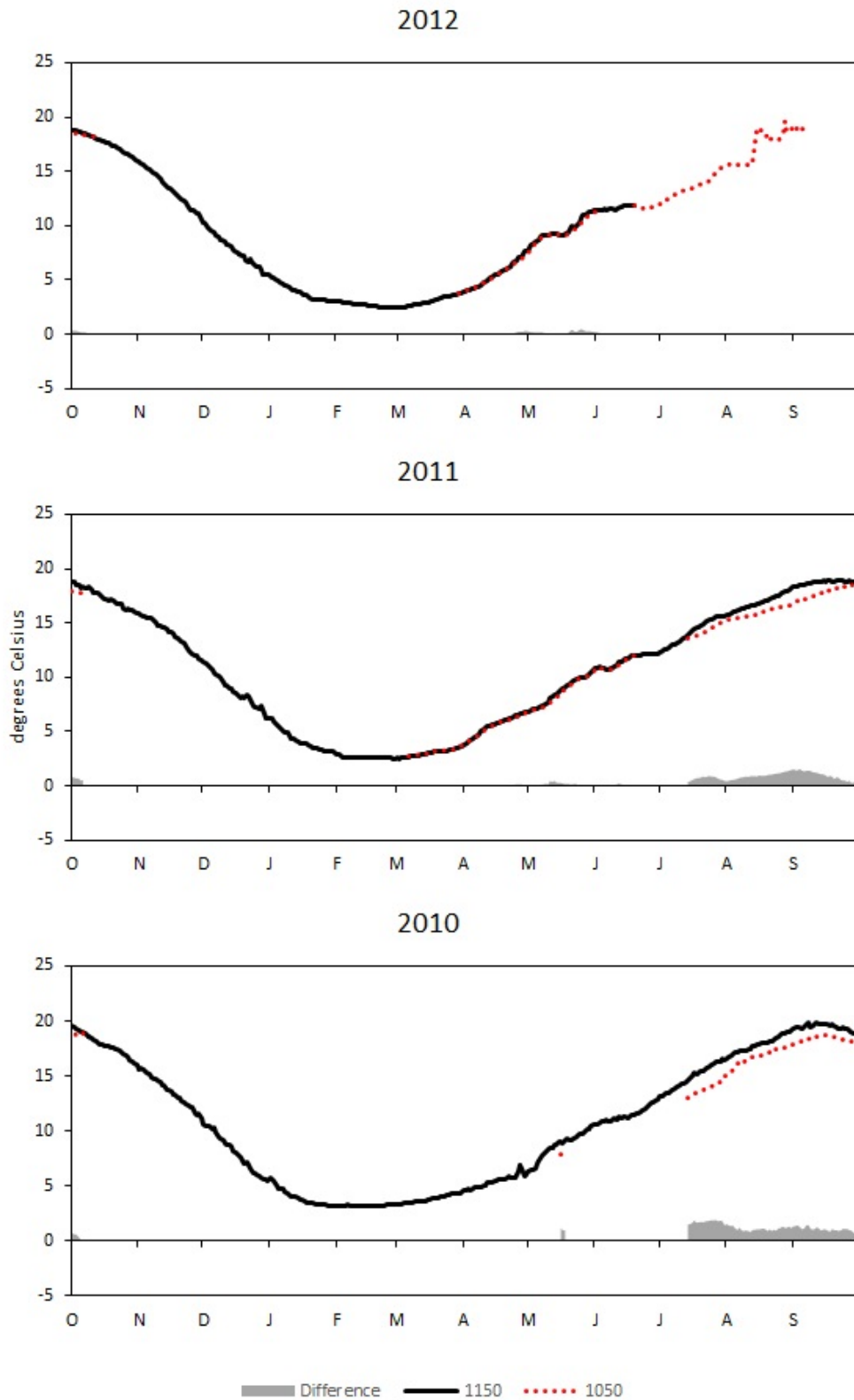


**Figure 5-18. Lake Roosevelt thermal stratification for water year 2000.**

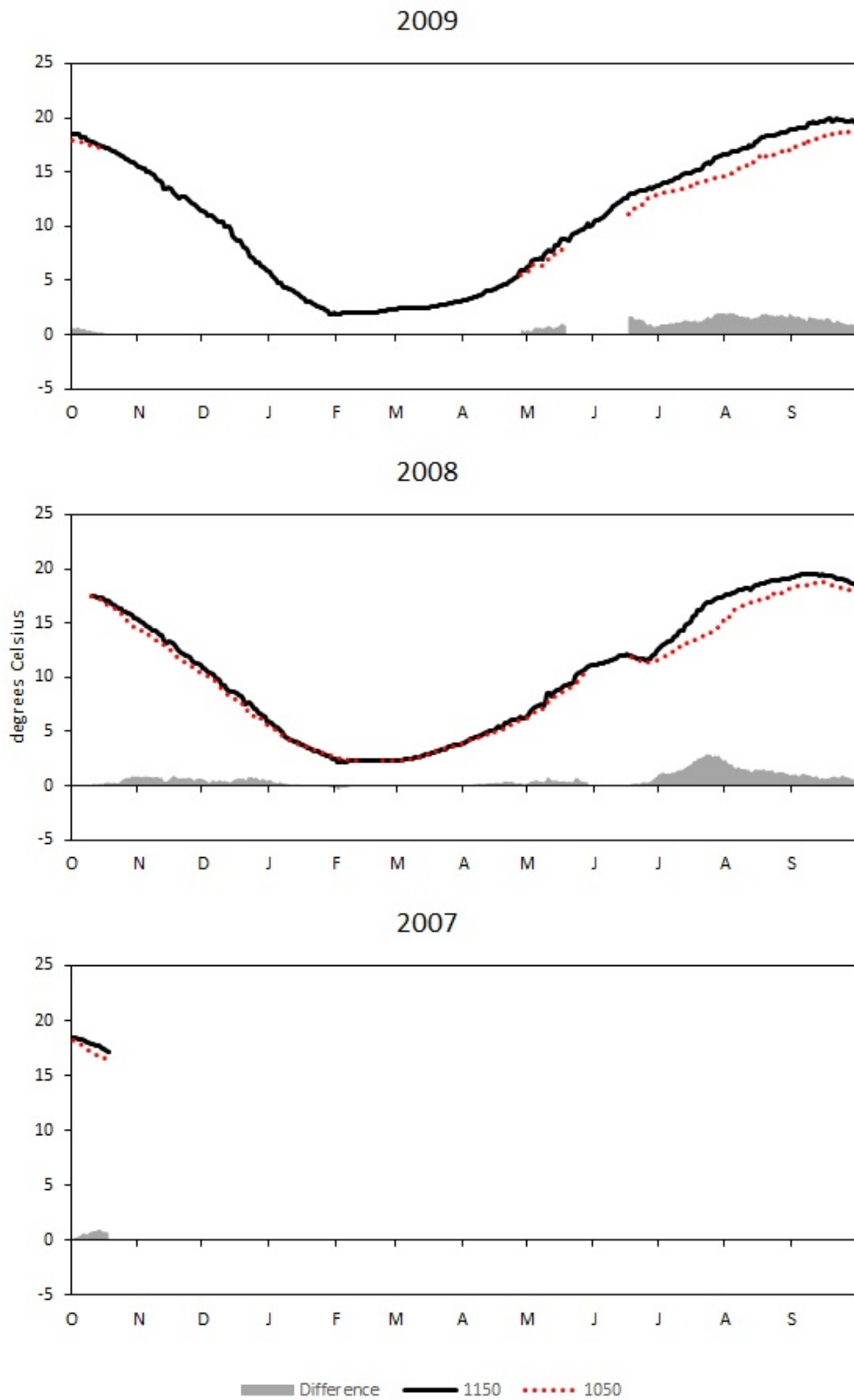
Figure 2-19 through Figure 5-24 depict the temperatures (from 2015 to 2000) at the approximate forebay elevations of the intakes for the Left and Right Power plants (1,050 feet elevation is used here as an approximation of the pool temperature at this intake, at elevation 1,040 feet) and the Third Power 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.**

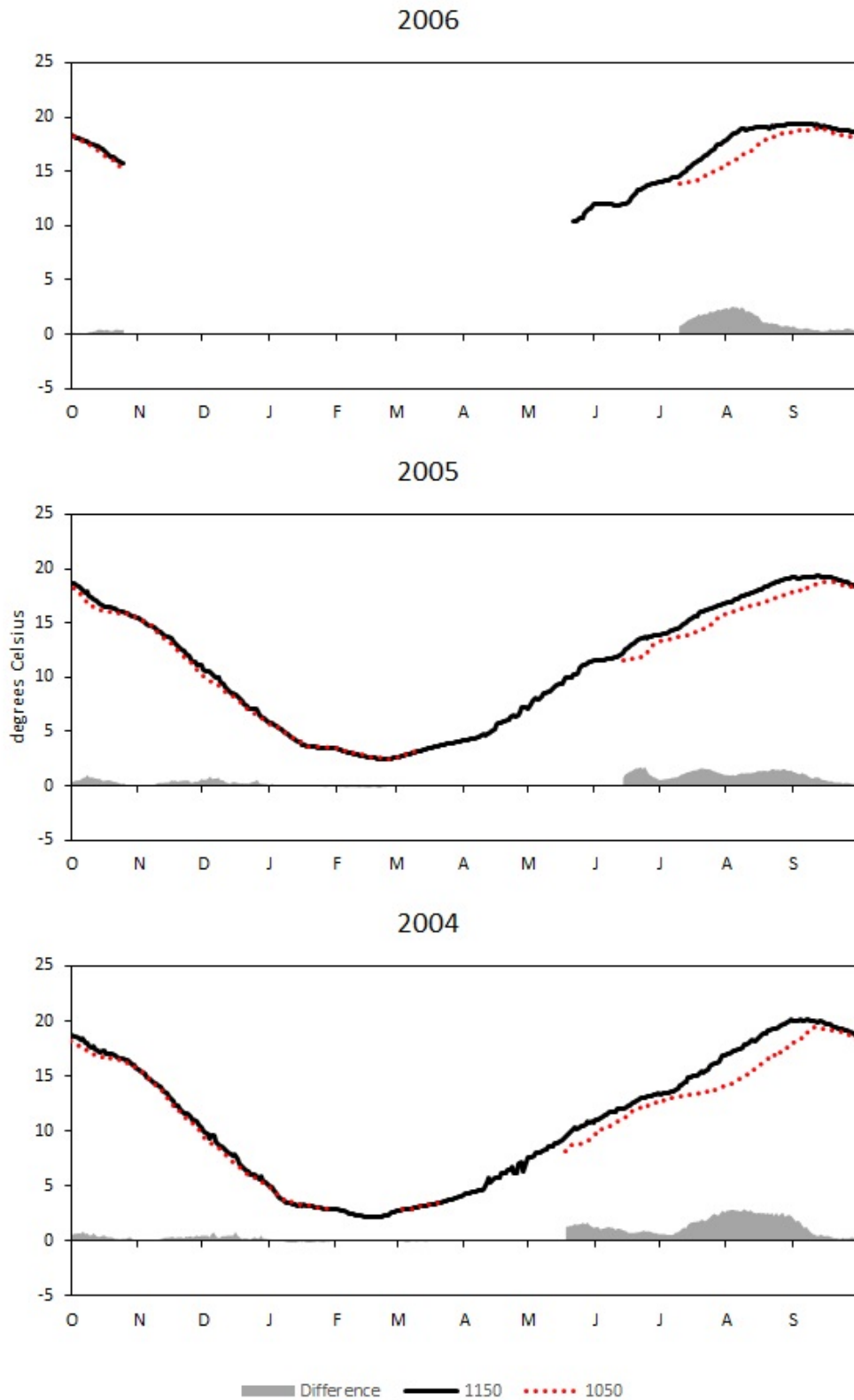


**Figure 5-20. Temperatures dating from 2012 to 2010 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**

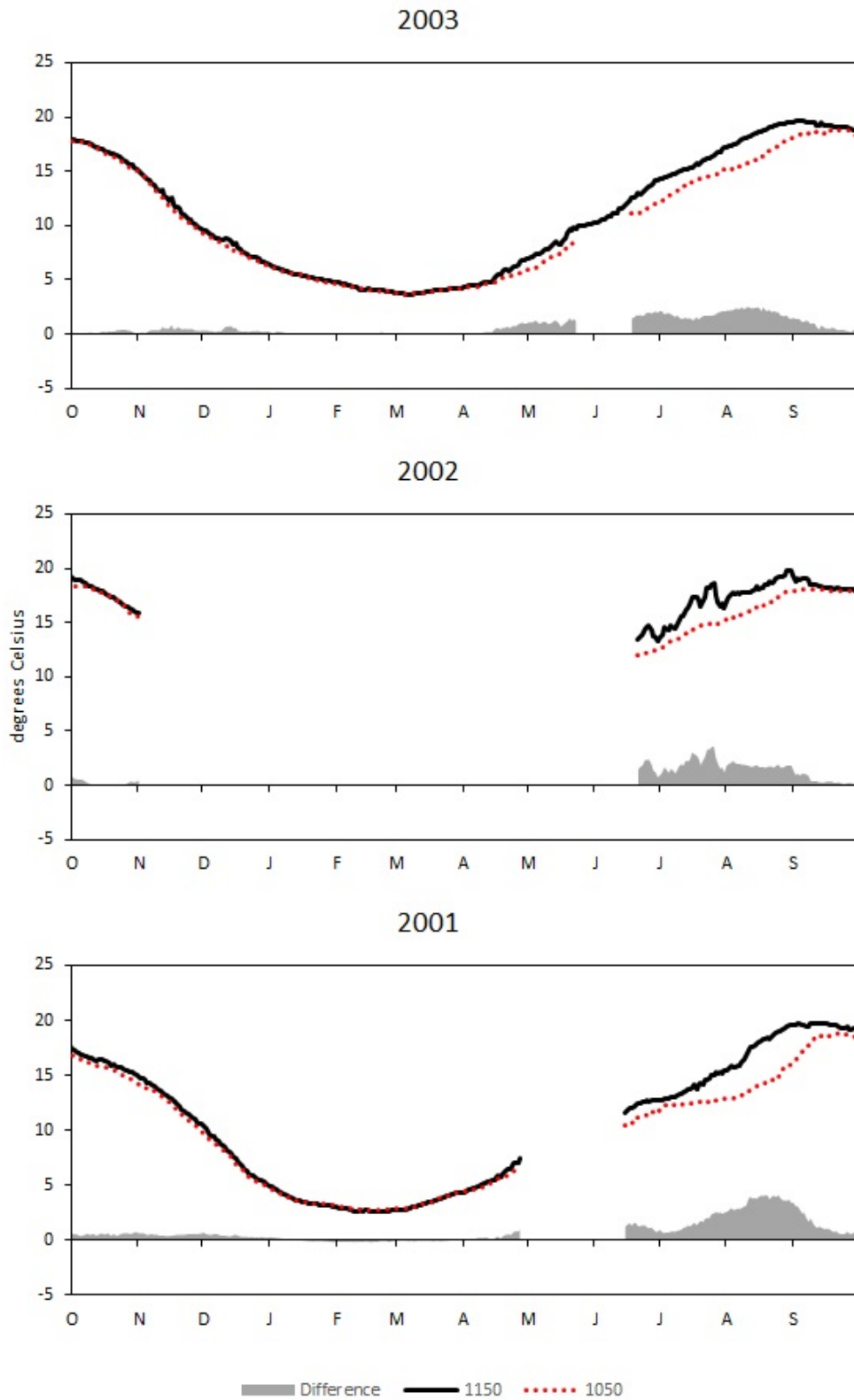


**Figure 5-21. Temperatures dating from 2009 to 2007 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**

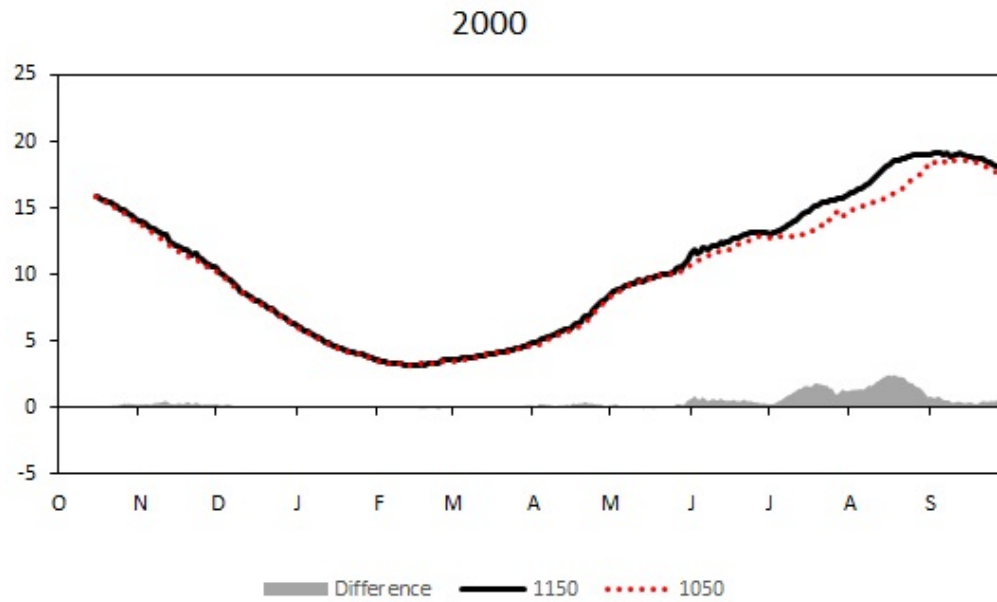




**Figure 5-22. Temperatures dating from 2006 to 2004 at the approximate forebay elevations of the intakes for the Left and Right and Third Power Plants.**



**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.**

*Page intentionally left blank.*