Technical Memorandum
Date: March 24, 2020
To: Cold Water Refuges Team
From: Martin Merz, John Palmer, and Alex Clayton
Subject: Characterization of Columbia River Temperature Variability

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This memorandum discribes the lognitundinal, seasonal, interannual, vertical, and daily temperature variation in the Lower Columbia River from the confluence with the Snake River to the ocean.

Longitudinal Temperature Variability in the Lower Columbia River

The Columbia River is a large low-lying river, which enters the State of Washington from Canada and warms as it moves through Washington towards the Pacific Ocean. ***Figure 1***, assembled with NorWeST data, illustrates this longitudinal warming in the summer month of August when river temperatures are at their seasonal peak. When the river enters Washington, average August river temperatures generally fluctuate between 17-18°C from year to year. Throughout the Lower Columbia River, where the river serves as the border between Washington and Oregon, the river fluctuates between 21-22°C. The lower section of the river is the corridor through which all Columbia Basin adult salmon migration must begin and is the focus of EPA's Cold Water Refuges project.

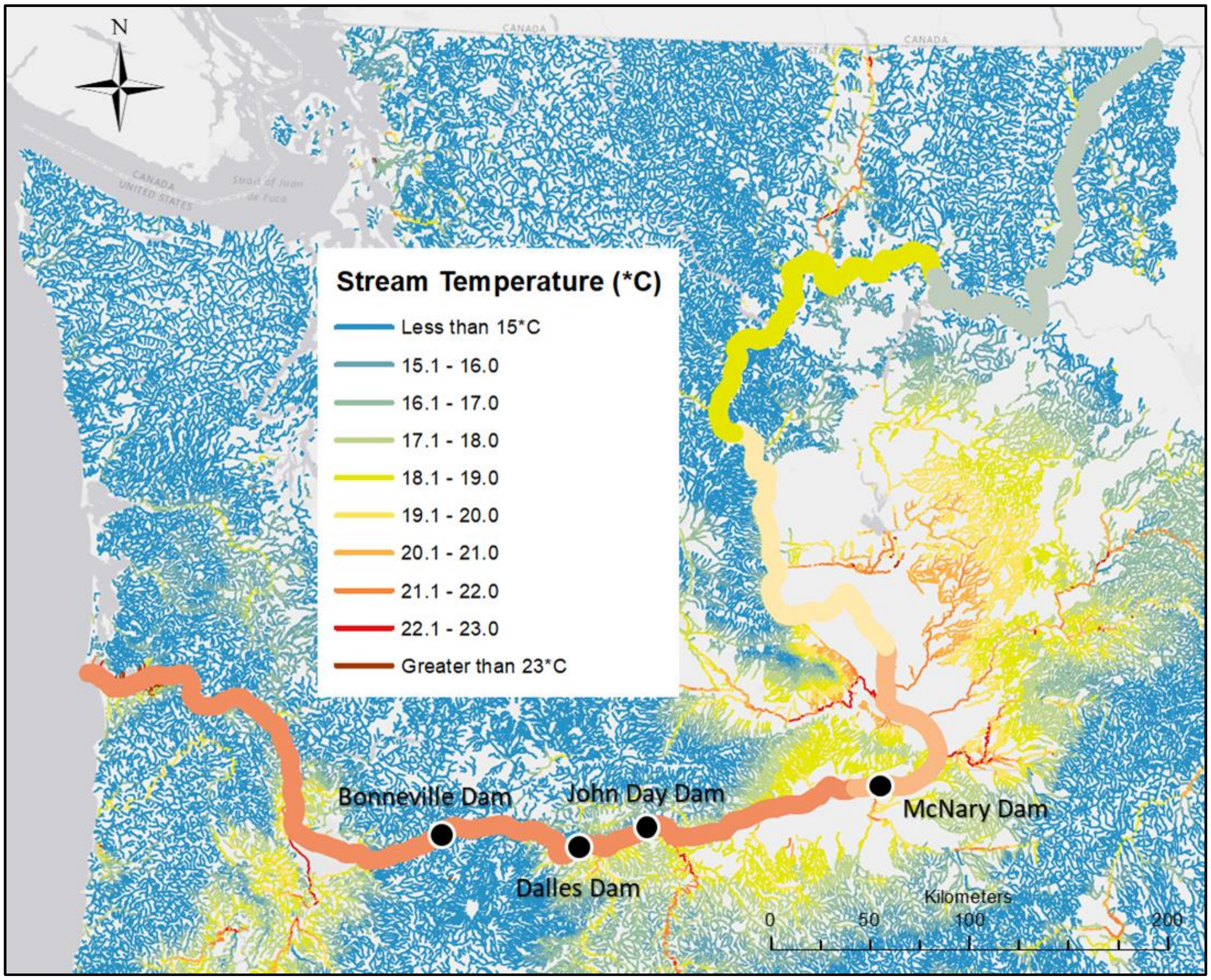

Figure 1 Current August Mean Water Temperature in the Columbia River and tributaries (2011-2016) (DART)

Columbia River DART (DART) data from the forebay (upstream) and tailrace (downstream) of each Lower Columbia River Dam was utilized to provide a closer look at the longitudinal temperature regime in the Lower Columbia River (***Figure 2***). The August data was averaged for the years 2011-2016. The forebay and tailrace data were already similar at any given dam but was averaged for this analysis. Thirty-five river miles upstream of McNary Dam, the Columbia River mixes with its largest tributary, the Snake River, which is warmer albeit smaller than the Columbia. By the time the Columbia River reaches McNary Dam, the most upstream of the four Lower Columbia River dams, the average August temperature is 21°C. The Columbia River then warms by 0.5°C on average in the 80-mile pool between McNary Dam and John Day Dam. The highest average August temperatures in the Lower Columbia River, and the whole Columbia River for that matter, occur near the John Day Dam, reaching 21.5°C on average in August. Temperatures then decrease slightly at The Dalles Dam and Bonneville Dam from the high temperatures at John Day Dam (***Figure 2***).

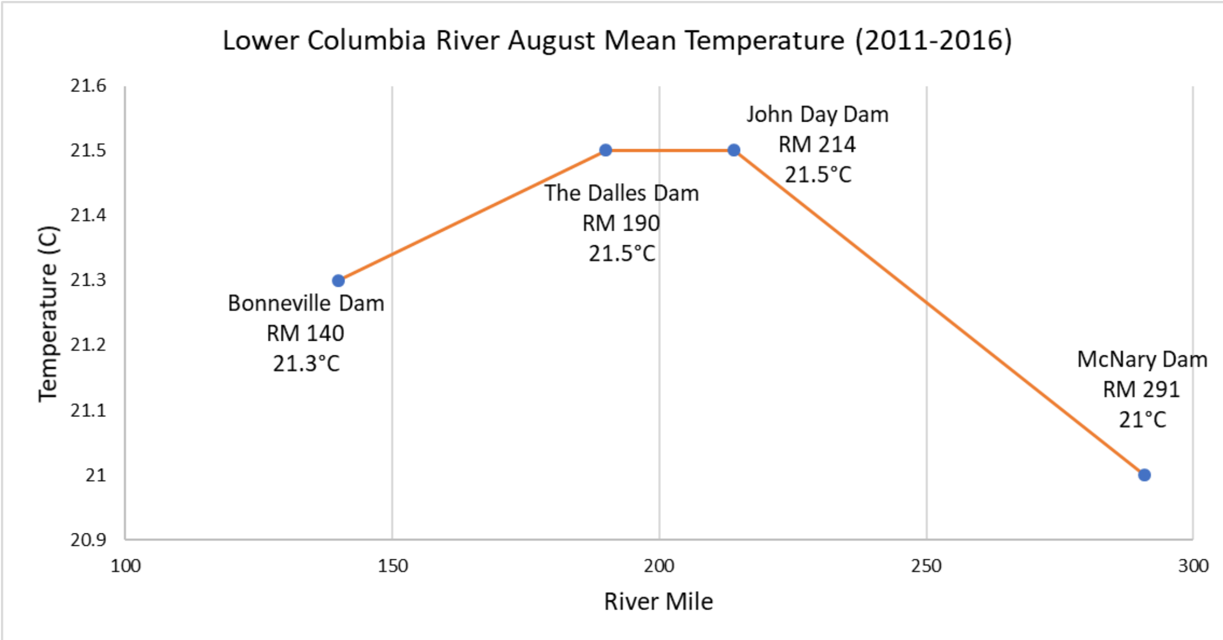

Figure 2 Longitudinal profile of the August Mean Columbia River Temperature from McNary Dam to the Bonneville Dam (2011-2016) (DART)

Figure 3 illustrates the six-year (2011-2016) observed daily average temperatures at the tailrace (downstream side) of the same four Columbia River dams, McNary (MCPW), John Day (JHAW), The Dalles (TDDO) and Bonneville (WRNO). Also illustrated in ***Figure 3*** is the 20°C water quality standard for the whole Lower Columbia River, developed by both Washington and Oregon to be protective of migrating salmon. Daily average temperatures typically exceed 20°C for 2 months in a given summer on average throughout the Lower Columbia River, from the middle of July to the middle of September. Further, temperatures exceed 21°C for one month on average, generally the month of August, and peak close to 22°C during this time. Average temperatures are slightly cooler at McNary Dam, due to the longitudinal warming pattern in the Lower Columbia River visible in ***Figure 2***, which is also observable in ***Figure*** 3.

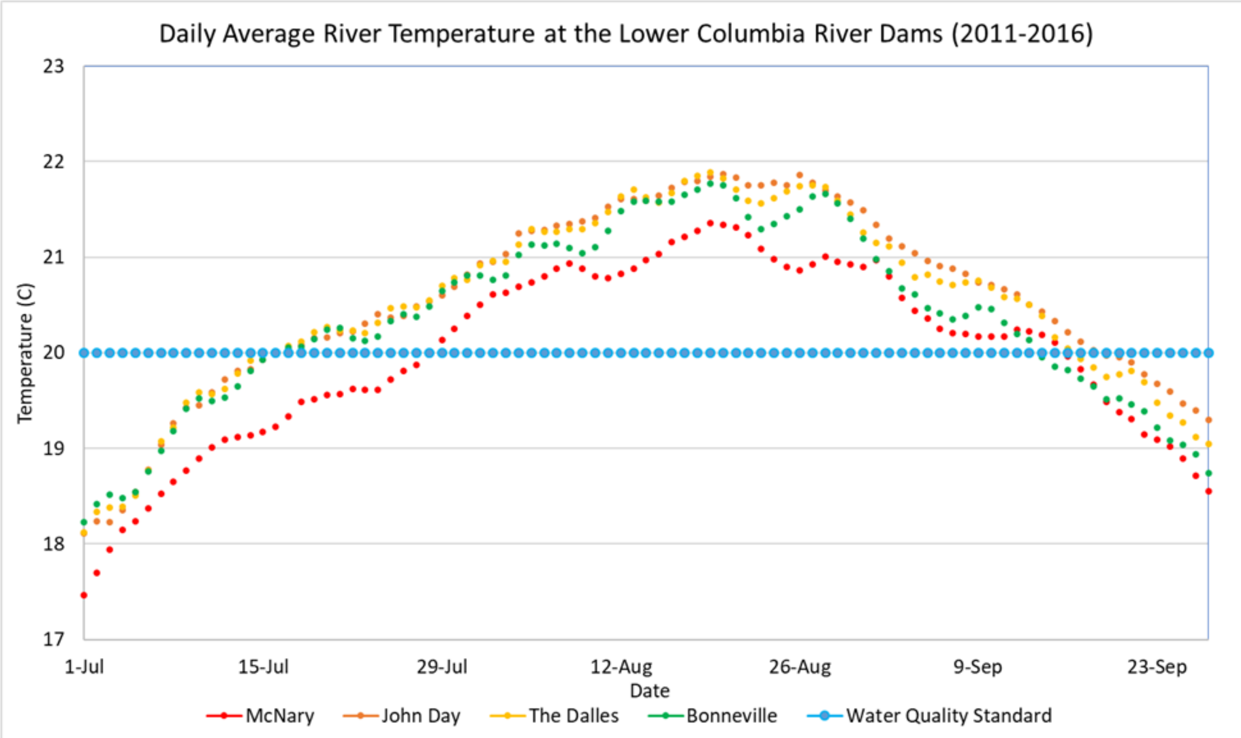

Figure 3 Lower Columbia River Temperature from early July to mid-September, 6-year average 2011-2016 (DART)

Upstream of McNary Dam (RM 291) is the Snake River confluence with the Columbia River (RM 325). The six-year daily average temperatures at McNary Dam (MCPW) are a function of the Columbia River temperature in Pasco (PAQW; just upstream of the Snake confluence) and the temperature of the smaller Snake River at Ice Harbor (IDSW; just upstream of the confluence), in addition to any longitudinal warming between the confluence and McNary Dam. The Snake River flow is generally close to 20% that of the Columbia River in July and August, so the temperature of the Columbia River has a larger impact after mixing. ***Figure 4*** illustrates this blending, showing the Columbia River (yellow) mix with the smaller yet warmer Snake River (blue) leading to the temperature at McNary Dam (MCPW), along with longitudinal warming between the confluence and McNary Dam.

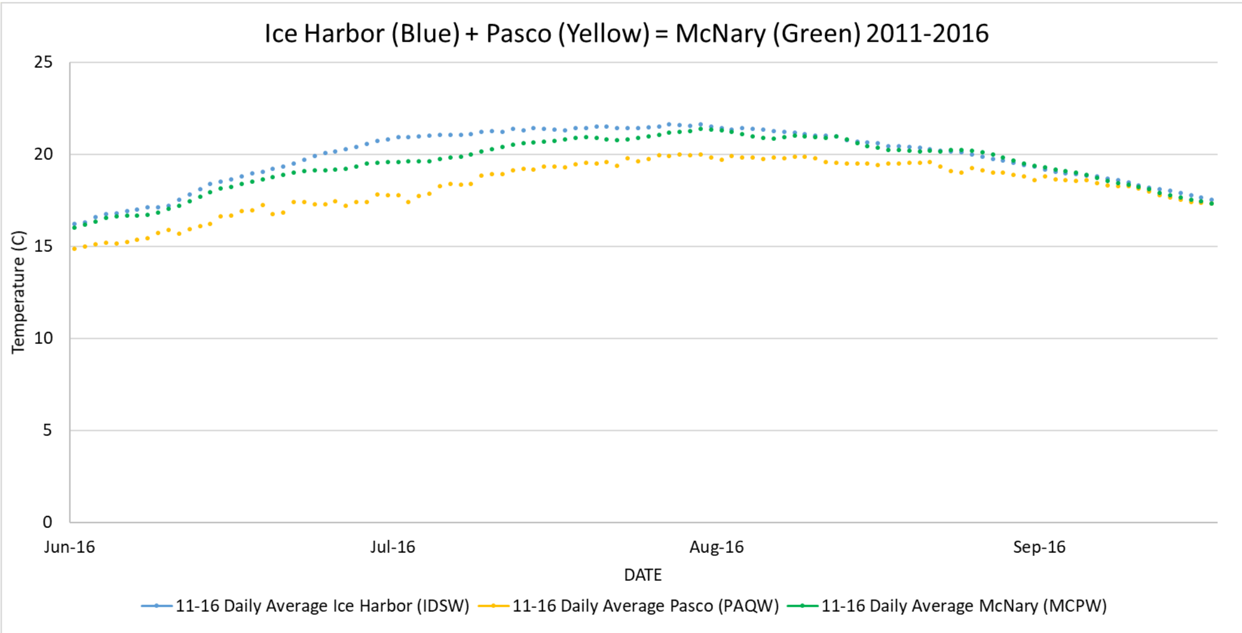

Figure 4 Influence of the Snake River (IDSW) and Columbia River as measured upstream of the Snake confluence in Pasco (PAQW) on the Lower Columbia River as measured at McNary Dam (MCPW) (DART)

Consistent temperature measurements are limited below Bonneville Dam. ***Figure 5*** illustrates that 10-year daily average temperatures below Bonneville Dam at Cascade Island (CCIW) and Camas/Washougal (CWMW) are about the same as Bonneville forebay (BON) temperatures, suggesting very little change in river temperatures below Bonneville Dam.

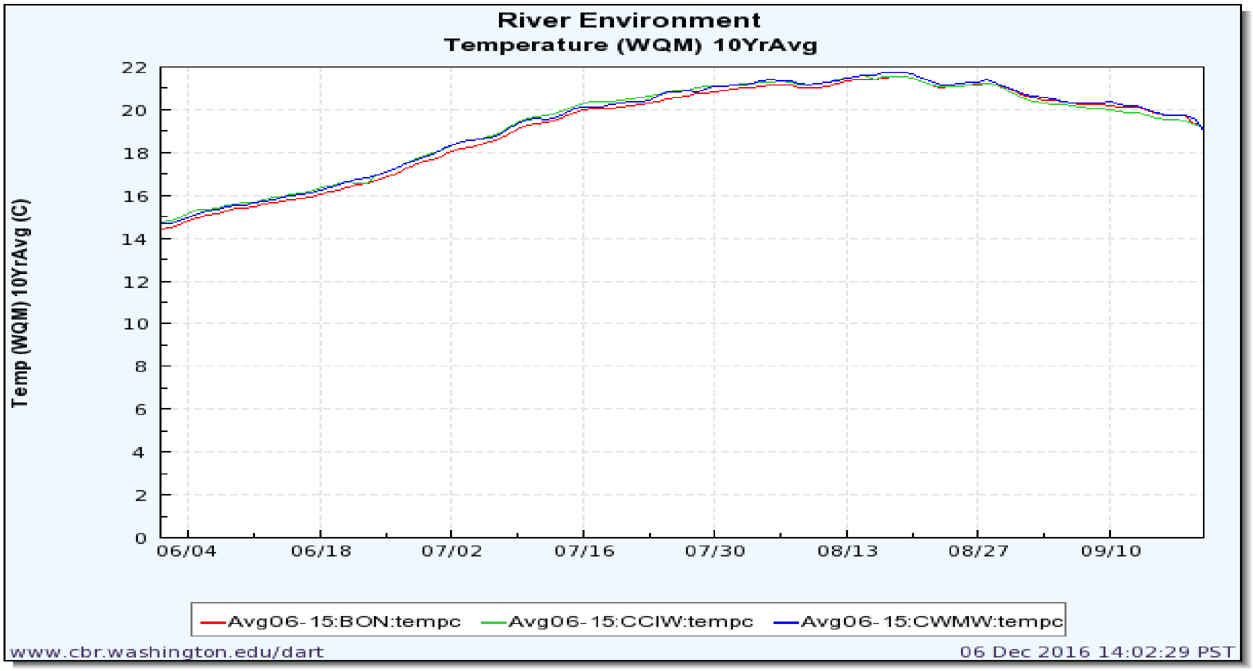

Figure 5 10 year average temperature at Bonneville Dam compared with temperatures slightly downstream at Cascade Island and Camas/Washougal (DART)

Daily average temperatures further downstream at Kalama (KLAW) compared to Bonneville forebay (BON) show very similar temperature profiles in 1996 – 1998, when temperatures were recorded at Kalama (see ***Figure 6***). This, along with ***Figure 5*** above, indicates that Bonneville Dam forebay temperatures are representative of Columbia River temperatures downstream of Bonneville Dam.

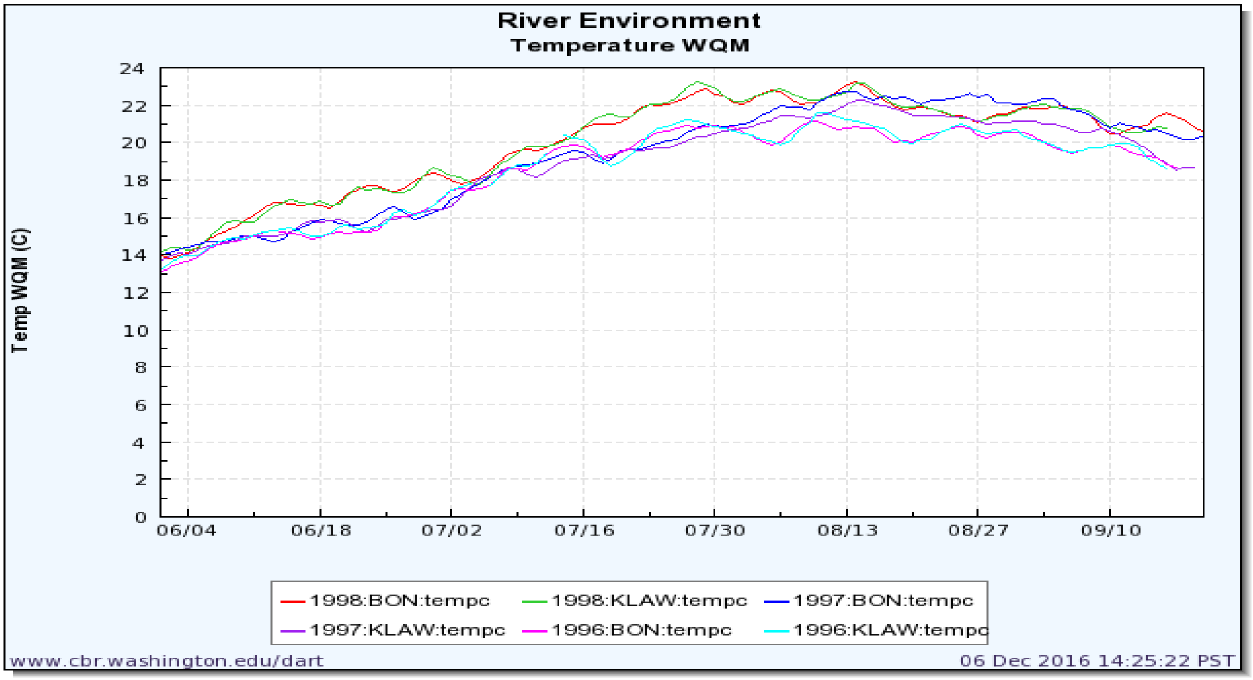

Figure 6 1996, 1997 and 1998 average temperature at Bonneville Dam compared with temperatures downstream at in Kalama (DART)

Seasonal and Interannual Temperature Variability in the Lower Columbia River

The figures above illustrates the temperature regime of the Columbia River averaged over multiple years, but it is important to note that this seasonal temperature profile can look very different between years due to different timing and magnitude of flows, different timing and intensity of warm weather and other factors. ***Figure 7*** shows the seasonal temperature profile downstream of Bonneville Dam (WRNO) for 10 individual years (2009-2018), illustrating the range that is observed in this seasonal temperature profile. These Bonneville daily average temperatures typically reach 20°C in mid July (thick black line), rise to 21-22°C in August, and fall below 20°C in early September.

The timing, duration and peak of warming can vary substantially year to year, and these characteristics relative to the timing of fish runs is very important in the context of cold water refuges. In mid-July, temperature ranged from about 17.5°C in 2011 (blue line) to 22.5°C in 2015 (red line) during this 10-year timeframe, a spread of 5°C (***Figure 7***). In mid-August when cold water refuge use is of particular importance, temperatures have less interannual variablity ranging from 20-22°C, more reliably exceeding the 20°C water quality standard. As an individual example year, 2015 (red line) warmed very early and peaked very early, but come the month of August when cold water refuge use is of particular importance, 2015 more closely matches average temperatures. The relatively cool summer of 2011 is an example of the river warming late, only exceeding 20°C for closer to a month and peaking at a much lower temperature than average.

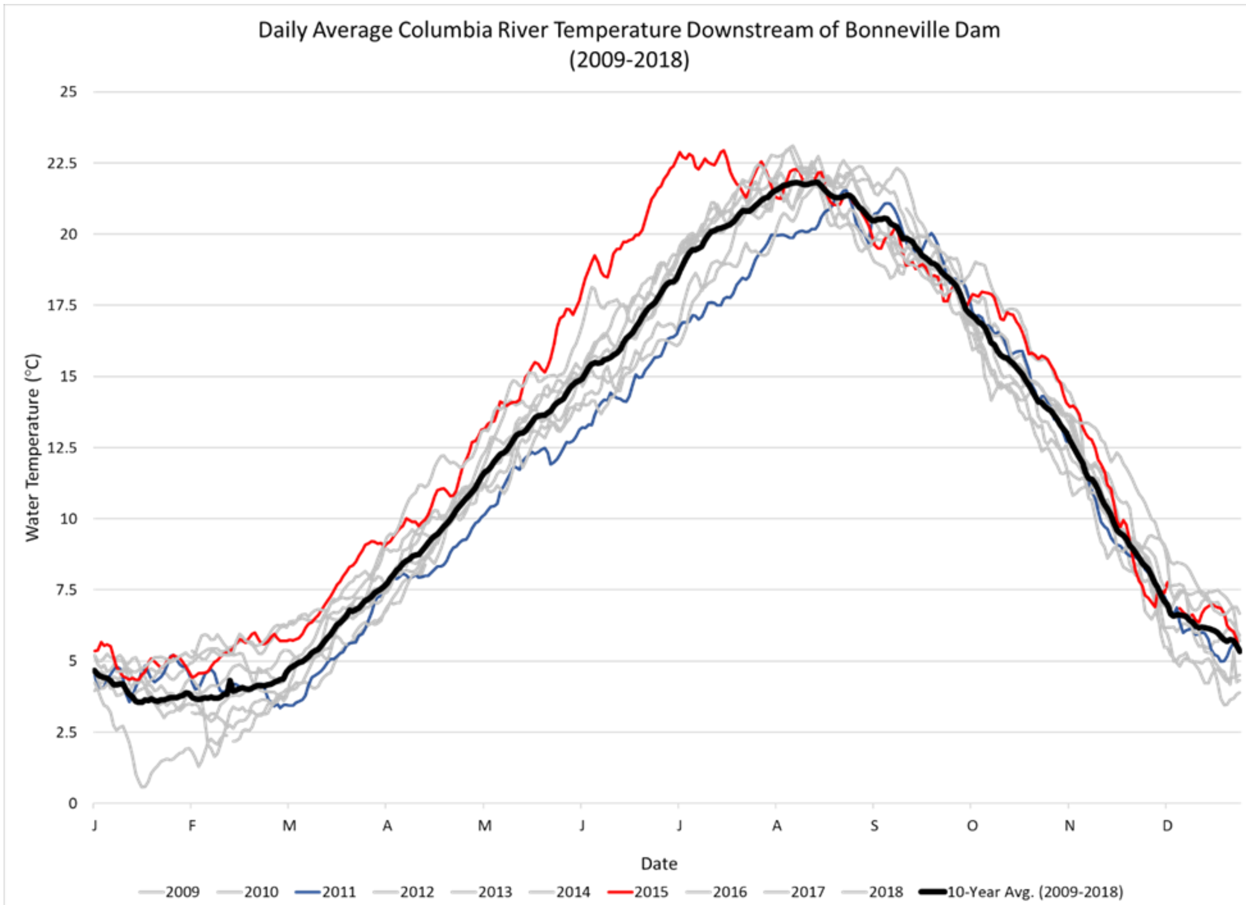

Figure 7 Seasonal temperature profiles downstream of Bonneville Dam, 10-year average 2009-2018 (DART)

Difference Between the August Mean and August Maximum Temperature

Since temperatures in the Lower Columbia River typically peak in the month of August, the August mean temperature is a common metric to characterize annual maximum temperatures in the Lower Columbia River. To characterize the difference between the August mean temperature and the maximum August temperature, **Table 1** shows the August mean and maximum hour temperature for the John Day Dam forebay for 2011 through 2019. As shown in **Table 1**, the difference between the August mean and the maximum August hour temperature is typically about 1.1C. ***Figures 8 - 11*** show the August hourly temperatures for the years 2016-

2019 which depict the range of hourly temperatures in the John Day Dam forebay, with the difference between the August mean and the maximum hour typically about 1C.

Table 1 and **Figures 8-11** also show that since 2013, the August mean at the John Day Dam forebay has been around 22°C and the maximum hourly temperature has been around 23°C.

Table 1 John Day Dam Forebay August Temperatures (DART)

Year	August Mean	August Maximum Hour	Difference
2011	20.5	21.7	1.2
2012	20.8	22.2	1.4
2013	22.1	23.1	1.0
2014	22.1	23.2	1.1
2015	21.9	22.6	0.7
2016	21.9	23.1	1.2
2017	22.6	23.5	0.9
2018	22.2	23.2	1.0
2019	22.1	23.1	1.0
Average	21.8	22.9	1.1

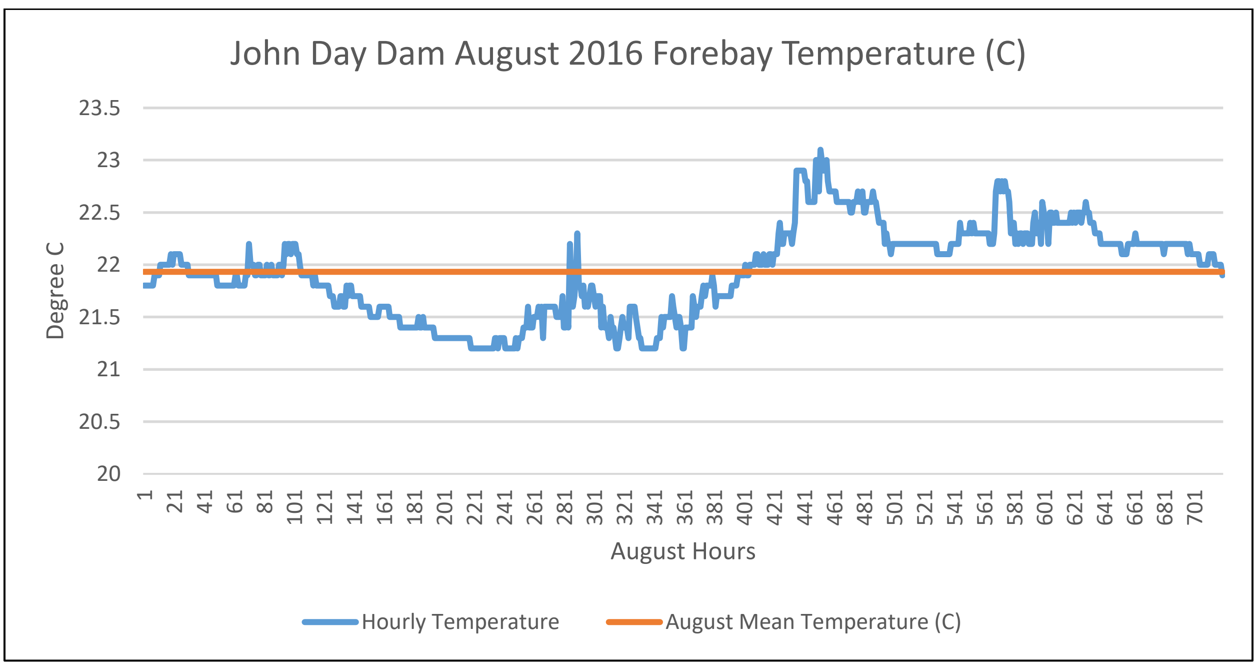

Figure 8 John Day Dam Forebay Hourly and August Mean Temperature (2016) (DART)

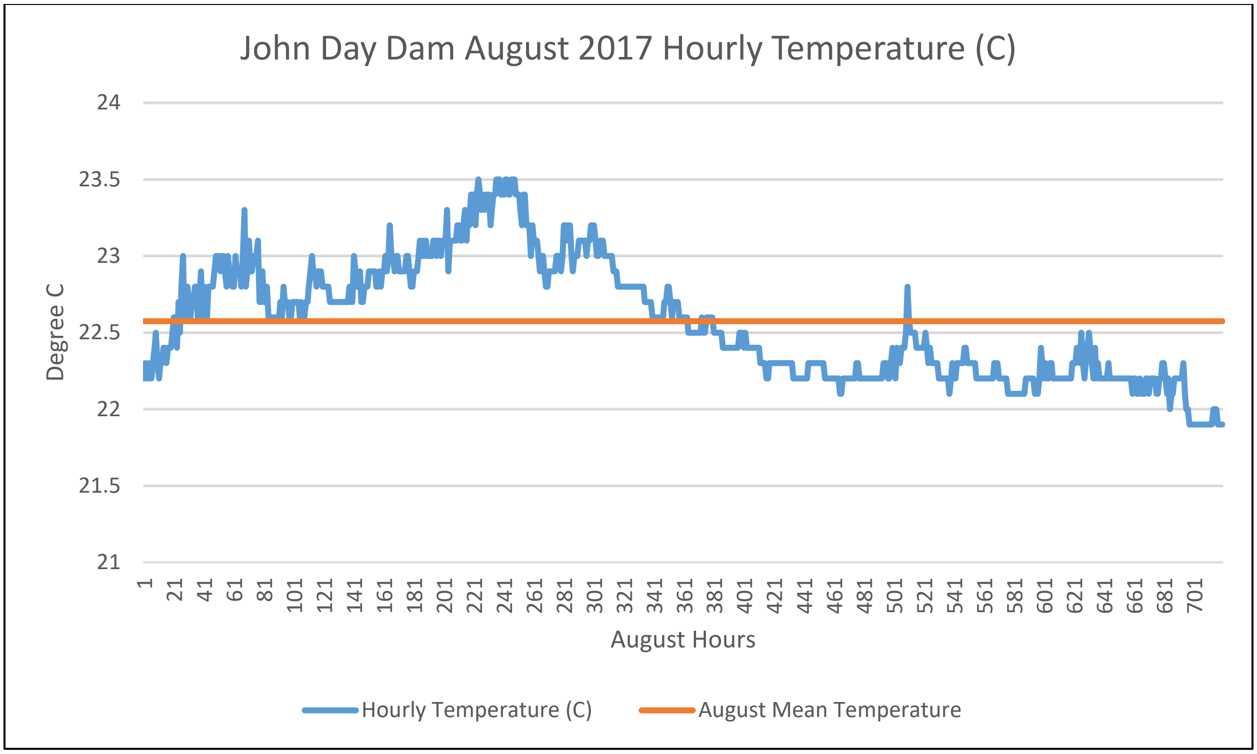

Figure 9 John Day Dam Forebay Hourly and August Mean Temperature (2017) (DART)

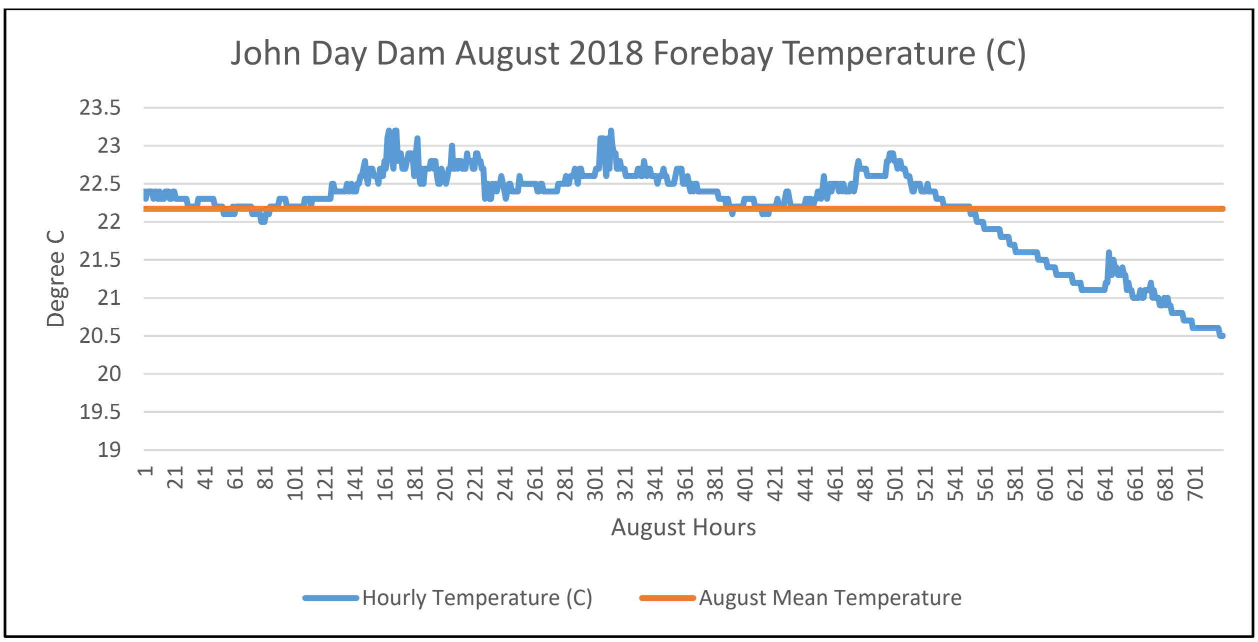

Figure 10 John Day Dam Forebay Hourly and August Mean Temperature (2018) (DART)

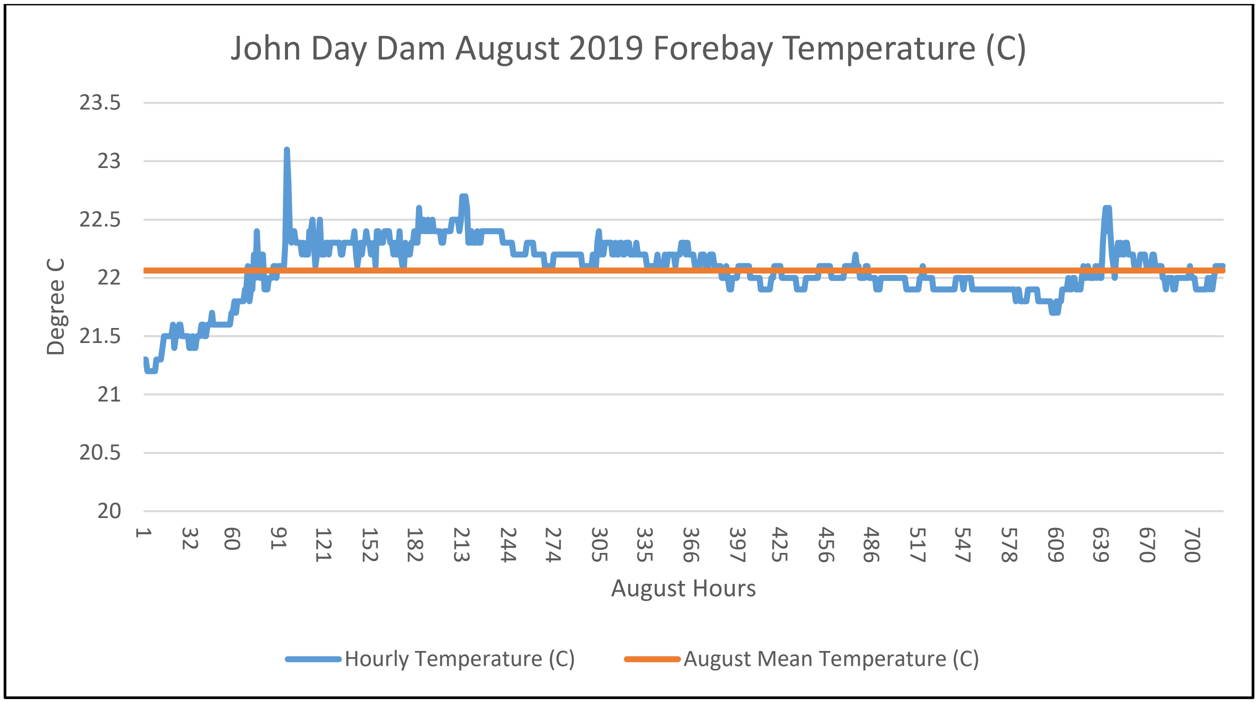

Figure 11 John Day Dam Forebay Hourly and August Mean Temperature (2019) (DART)

Vertical Temperature Variability in the Lower Columbia River

The following figures and tables (***Figures 12-24 and Tables 2 and 3***) show degree to which the reservoirs behind each the four Lower Columbia River dams have a thermal gradient or stratification where the surface is warmer than the bottom. ***Figure 12 and 13*** show there is very little difference in temperature between the top and the bottom of the Bonneville Dam forebay with no significant temperature gradient. Similarly, ***Figures 14 and 15*** show there is very little temperature gradient in The Dalles Dam forebay.

In contrast, ***Figures 16 and 17*** show a significant difference temperatures gradient in the John Day Dam forebay. ***Figure 17*** shows the difference between the surface (5 feet depth) and near the bottom (100-foot depth) to be in the 2.3–3.3°C (4°F-6°F) range on numerous summer days in 2018 and as high as 4°C (7-8°F) on a couple of days. As shown in ***Figure 16***, temperatures near the surface (5-foot depth) in the John Day forebay reached 25-25.6°C (77-78°F) on a few days in 2018, while the temperatures at 100-foot depth were in the 22°C (72-73°F) range on those days.

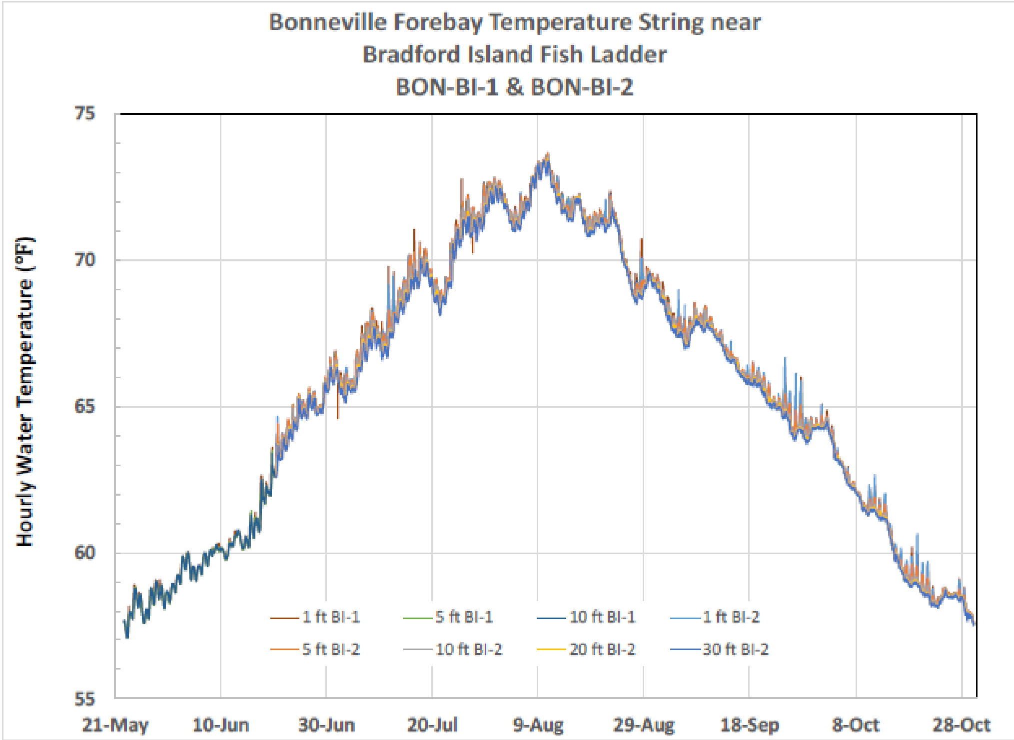

Figure 12 Bonneville Forebay Hourly Vertical Profile Temperatures Measured from the Wall Mounted and Floating Strings near the Bradford Island Fish Ladder Exit, May 23 - October 30, 2018 (Figure 5-14 in USACE, 2019)

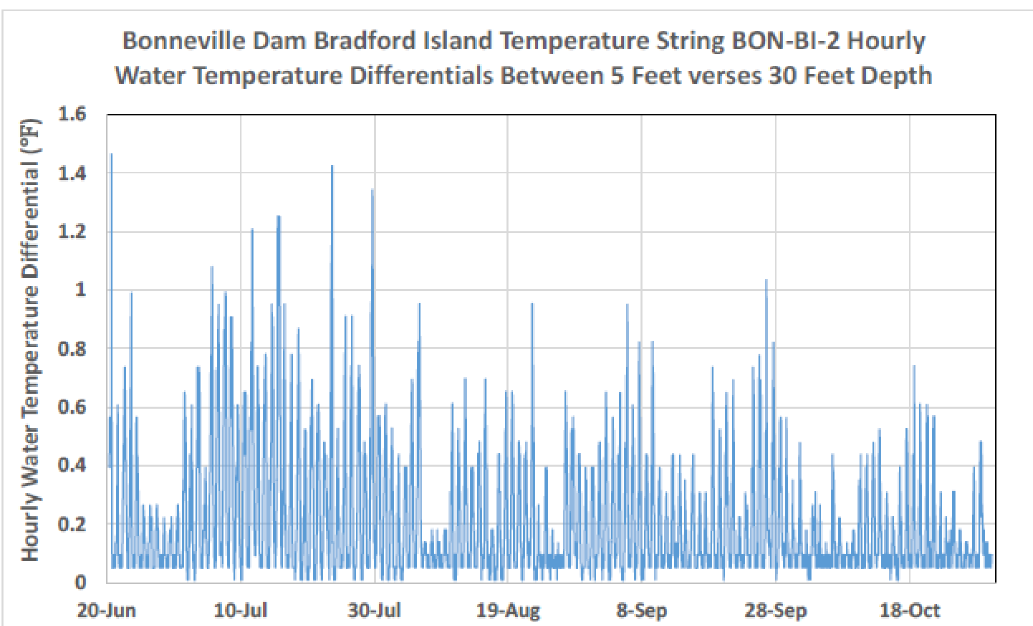

Figure 13 Bonneville Dam at Bradford Island Hourly Vertical Profile Temperatures Differentials BON-BI-2 Calculated between 5 Foot and 30 Foot Depths, June 20 - October 30, 2018 (Figure 5-15 in USACE, 2019)

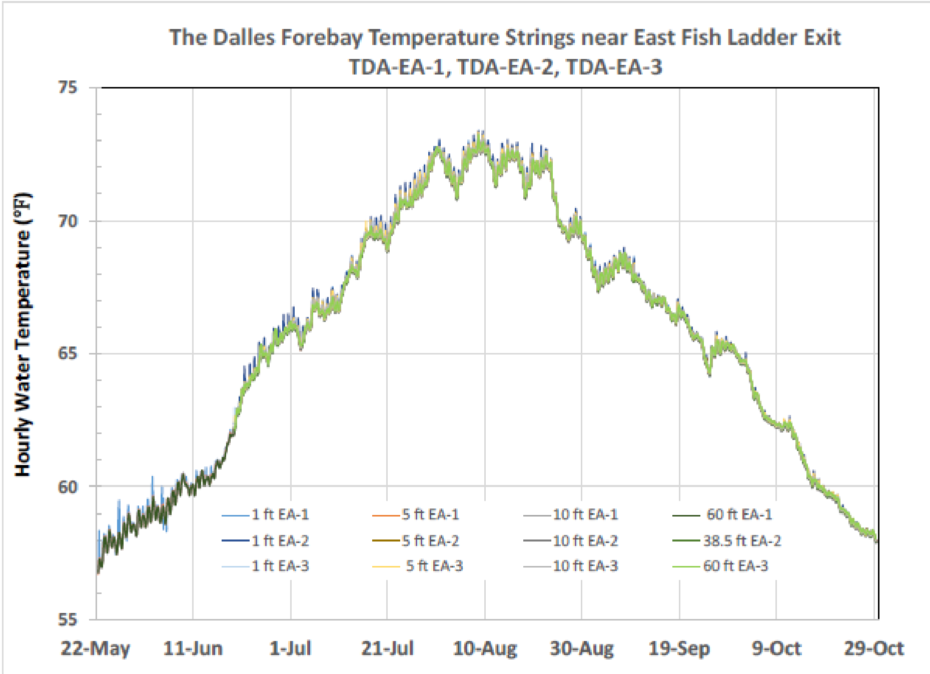

Figure 14 The Dalles Forebay Hourly Vertical Profile Temperatures Measured from the Wall Mounted and Two Floating Strings near the East Fish Ladder Exit, May 22 - October 29, 2018 (Figure 5-8 in USACE, 2019)

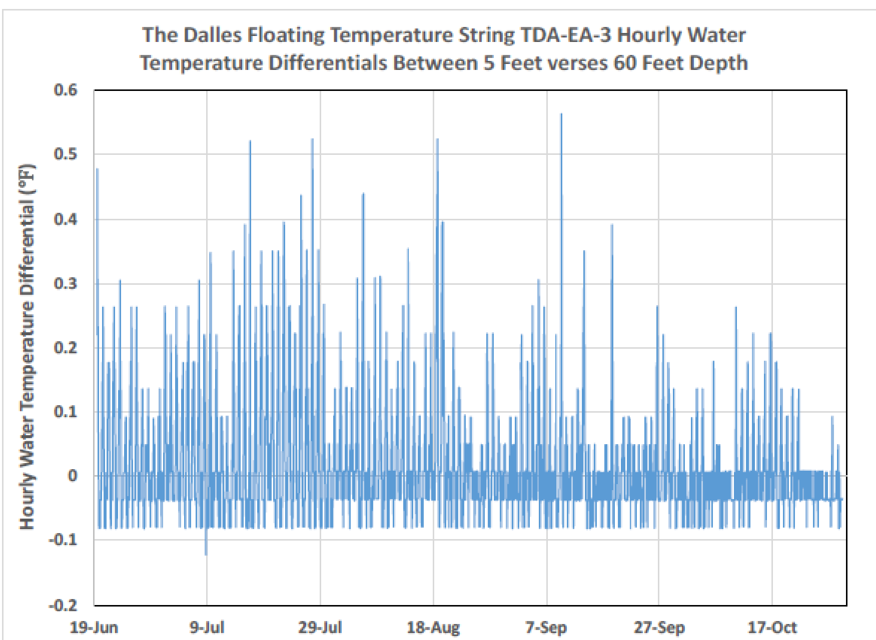

Figure 15 The Dalles Forebay Hourly Vertical Profile Temperatures Differentials for Floating String TDA-EA-3 Calculated between 5 Foot and 60 Foot Depths, June 19 - October 29, 2018 (Figure 5-9 in USACE, 2019)

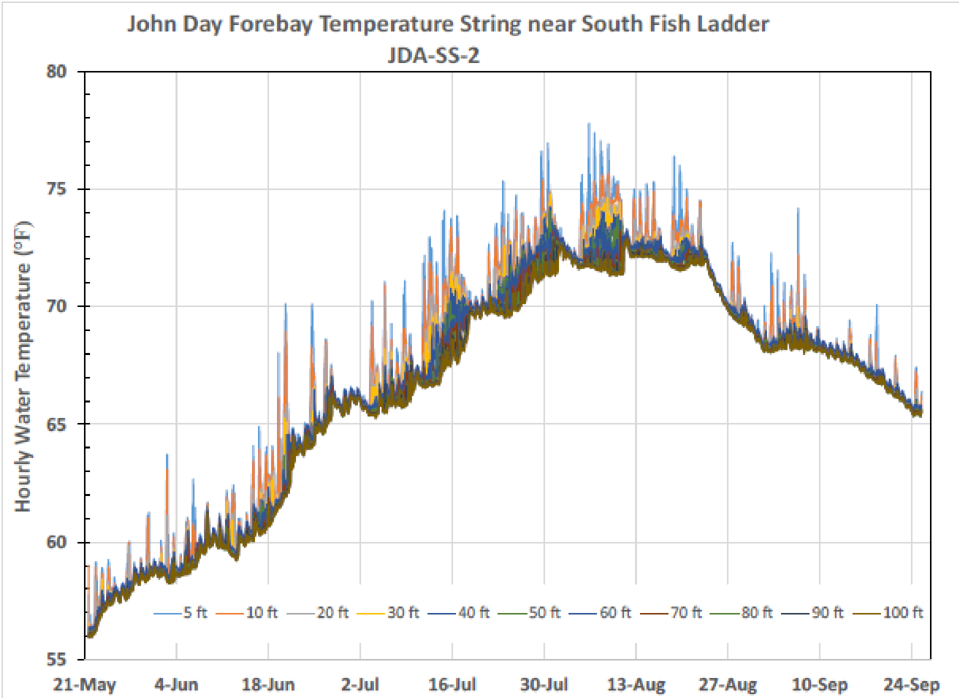

Figure 16 John Day Forebay Hourly Vertical Profile Temperatures Measured from the Dam Structure North of the South Fish Ladder Exit, May 21 - September 25, 2018 (Figure 5-2 in USACE, 2019)

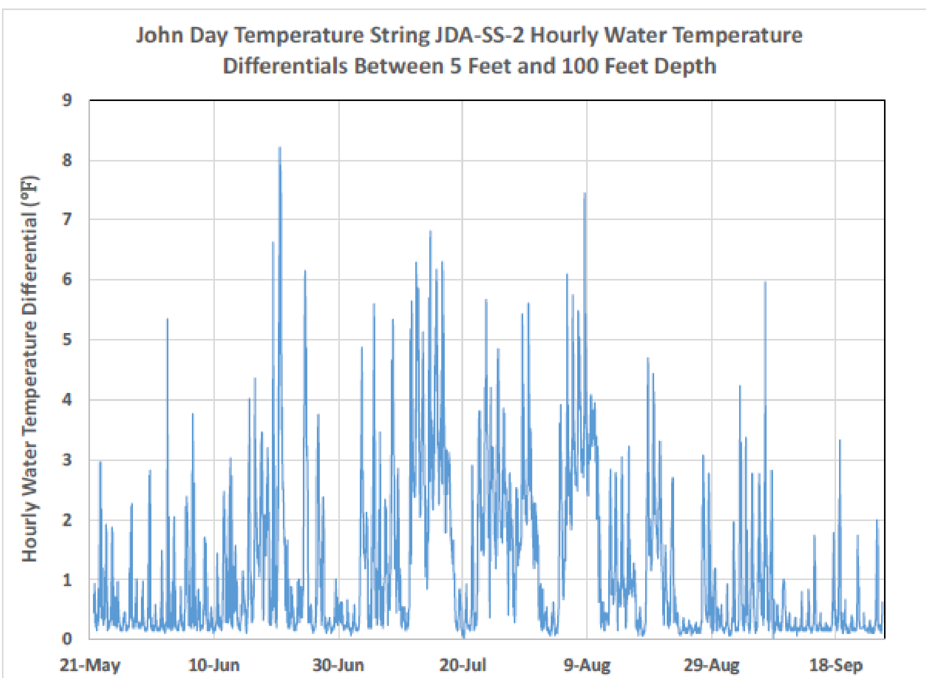

Figure 17 John Day Forebay Hourly Vertical Profile Temperatures Differentials JDA-SS-2 Calculated between 5 Foot and 100 Foot Depths, May 21 - September 25, 2018 (Figure 5-6 2 in USACE, 2019)

Tables 2 and 3 show the temperature at different depths within the McNary Dam forebay on August 1, 2015 and August 17, 2016, respectively, and show a significant temperature gradient on these days. On August 1, 2015 (***Table 2***), surface temperatures reached 28°C during the late afternoon-evening, while bottom temperatures remained below 21°C, resulting in a temperature difference of 7°C. Similar maximum temperatures and temperature different between the surface and the bottom occurred on August 17, 2016 (***Table 3***). These data show that the warmest temperatures were in the upper 3 meters (10 feet). String data collected by the Army Corps of Engineers demonstrates that a significant temperature gradient is a common occurrence in the McNary Dam forebay in the summer (USACE).

For reference, the McNary forebay fixed temperature monitor recorded a daily mean of 21.2°C on August 1, 2015 and on August 17, 2016. The fixed monitor is approximately 10 meters (30 feet) deep, so it does not capture the warmer temperatures in the upper 3 meters.

Table 2 McNary Forebay August 1, 2015(USACE String Data)

Time	0.5m	1.5m	3m	5m	10m	15m	20m	21m
00:00	24.21	23.83	21.72	21.05	20.82	20.69	20.66	20.51
01:00	23.87	23.62	21.74	21.11	20.86	20.75	20.66	20.52
02:00	23.49	23.46	21.66	21.05	20.89	20.73	20.67	20.54
03:00	23.09	22.91	21.64	21.13	20.88	20.73	20.68	20.55
04:00	22.99	23.05	21.66	21.30	20.89	20.79	20.70	20.56
05:00	22.77	22.87	21.71	21.06	20.89	20.79	20.68	20.57
06:00	22.60	22.65	21.63	21.03	20.91	20.80	20.71	20.59
07:00	22.53	22.36	21.68	21.12	20.92	20.80	20.71	20.60
08:00	22.46	22.20	21.40	21.15	21.03	20.77	20.70	20.61
09:00	22.65	22.17	21.33	21.13	21.04	20.82	20.74	20.62
10:00	22.69	22.57	21.72	21.38	20.89	20.81	20.75	20.62
11:00	23.68	22.36	21.91	21.63	20.92	20.85	20.75	20.63
12:00	24.04	22.83	21.65	21.56	20.93	20.86	20.76	20.64
13:00	25.34	22.73	22.25	21.55	20.92	20.84	20.75	20.66
14:00	26.45	23.45	22.78	21.82	20.94	20.81	20.73	20.66
15:00	28.25	23.90	22.87	21.29	20.90	20.80	20.72	20.66
16:00	27.88	24.02	22.08	21.39	20.89	20.83	20.76	20.67
17:00	28.15	24.72	23.02	21.56	20.88	20.82	20.74	20.67
18:00	27.92	24.33	22.61	21.93	20.88	20.83	20.76	20.67
19:00	27.53	24.54	22.62	21.43	20.85	20.80	20.75	20.69
20:00	26.83	24.95	22.47	21.68	20.85	20.79	20.77	20.70
21:00	25.54	24.41	22.91	21.51	20.84	20.78	20.74	20.68
22:00	25.36	24.73	22.90	22.04	20.84	20.79	20.75	20.68
23:00	25.06	24.80	22.60	21.81	20.91	20.79	20.78	20.68

Table 3 McNary Forebay August 17, 2016 (USACE String Data)

Time	0.5m	1.5m	3m	5m	10m	15m	20m	21m
00:00	25.30	25.34	23.55	22.25	21.06	20.99	20.88	20.79
01:00	24.97	25.01	23.45	22.16	21.05	21.01	20.90	20.81
02:00	24.65	24.73	23.25	22.24	21.09	21.00	20.88	20.82
03:00	24.38	24.50	23.67	22.18	21.12	21.04	20.91	20.84
04:00	24.44	24.48	22.90	22.30	21.12	21.03	20.90	20.87
05:00	24.23	24.31	23.59	22.39	21.13	21.07	20.93	20.88
06:00	24.13	24.17	23.62	22.55	21.15	21.06	20.92	20.88
07:00	24.08	24.15	23.39	22.44	21.26	21.08	20.96	20.88
08:00	24.02	24.10	23.38	22.27	21.34	21.04	20.97	20.88
09:00	24.10	24.14	23.46	22.43	21.34	21.08	20.99	20.88
10:00	24.20	24.19	23.43	22.26	21.35	21.07	20.94	20.87
11:00	24.40	24.35	23.70	22.25	21.15	21.07	20.95	20.87
12:00	24.49	24.25	23.73	22.02	21.38	21.06	20.95	20.87
13:00	25.10	24.30	23.39	22.07	21.36	21.08	20.99	20.89
14:00	25.52	24.56	23.82	22.53	21.31	21.08	20.97	20.90
15:00	26.64	25.05	24.07	22.80	21.28	21.09	21.00	20.91
16:00	27.92	25.62	23.84	22.61	21.44	21.10	20.99	20.90
17:00	27.39	25.81	23.95	22.64	21.21	21.06	20.94	20.89
18:00	27.10	25.62	24.10	22.58	21.21	21.11	20.95	20.88
19:00	27.00	25.60	24.09	22.73	21.28	21.03	20.95	20.90
20:00	26.58	26.06	24.19	23.02	21.33	21.05	21.02	20.89
21:00	26.35	25.79	23.82	22.82	21.29	21.09	21.00	20.91
22:00	25.63	25.51	23.78	22.98	21.22	21.12	20.98	20.92
23:00	25.35	25.47	24.10	22.83	21.18	21.11	20.98	20.93

Figure 18 shows measured and modeled temperatures in the four different locations in the McNary Dam forebay on August 18, 2004. Near the surface temperatures were around 25°C at 6pm and were about 22°C below 10 meters (30 feet). ***Figure 19*** provide a model profile of the McNary Dam forebay on August 18, 2004.

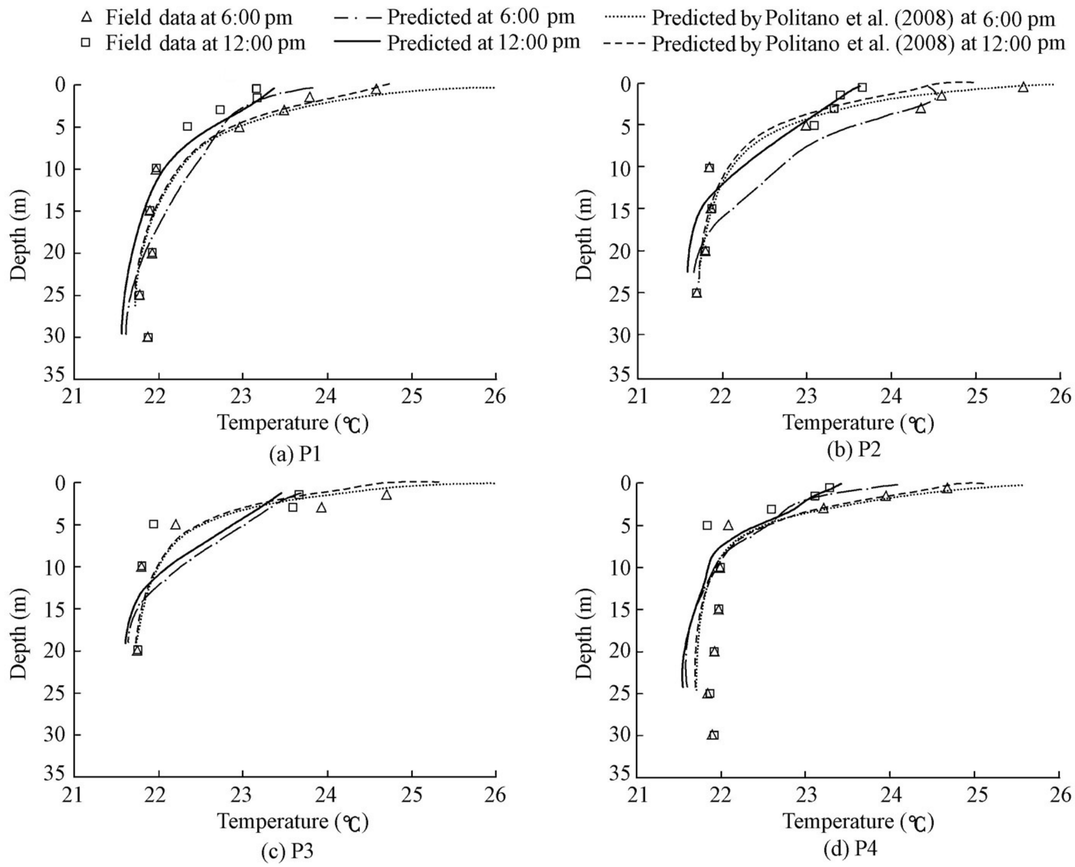

Figure 18 Temperature profiles at 6:00 pm and 12:00 pm for stations P1, P2, P3, and P4 in McNary Forebay on August 18, 2004 (Yu-shi Wang et al., 2013)

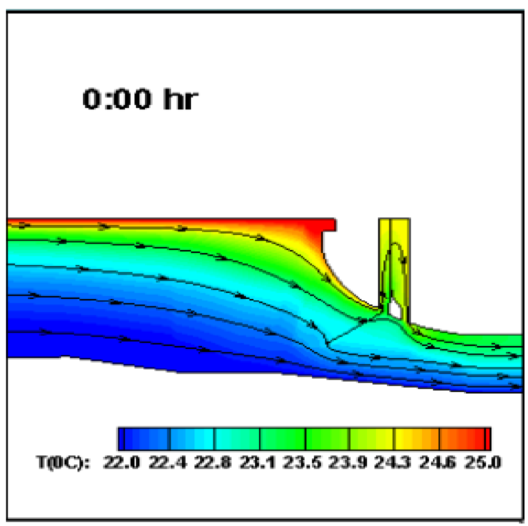

Figure 19 Dissection view of vertical temperature variability in the McNary Forebay on August 18, 2004 (M. Haque presentation of McNary Dam model and presented in Politano et al., 2008)

Figures 20-25 show predicted two-dimensional temperatures in the Lower Columbia River reservoirs on selected days based on the Army Corps of Engineers model. Consistent with the measured data shown above, ***Figures 20 and 21*** show significant thermal gradients in the McNary and John Day reservoirs on July 8 and July 10, 2015, respectively. On July 8, 2015, the McNary reservoir was modelled to exceed 26°C in McNary Dam forebay and exceed 24°C in upper portion of the lower half of the McNary reservoir, while temperatures in the deepest part of the reservoir were modeled to be in the 20-22°C range. On July 10, 2015, the John Day reservoir was modelled to exceed 27°C in John Day Dam forebay and exceed 24°C in upper portion of most of the John Day reservoir, while temperatures in the deepest part of the reservoir were modeled to be in the 20-22°C range.

Also consistent with measured data shown above, ***Figures 22 and 23*** show very little modelled thermal gradient in The Dalles and Bonneville reservoirs, on July 10 and July 15, respectively.

Figures 24 and 25 show modelled temperatures for the John Day reservoir for two additional days on August 5 and 18, 2014, respectively. Model results for August 5, 2014 (***Figure 24***) in the John Day reservoir are similar to those shown for July 10, 2015 (***Figure 21***), with the warmest temperatures in the forebay, warm temperatures in the upper part of the reservoir, and cooler temperatures in the deepest part of the reservoir. On August 18, 2014 (***Figure 25***) the model shows warmer temperature at the surface, especially in the forebay area, but the rest of the reservoir at about the same temperature.

The depth of the John Day Dam forebay continuous temperature monitor reflected in Columbia River DART is approximately 30-35 feet deep, so it reflects temperatures at approximately 1/3 the depth of the reservoir near the dam and does not reflect the warm surface temperatures. The continuous temperature monitor at this depth, however, does appear to be a good representation of the overall John Day reservoir temperature. For comparison, the John Day forebay monitor in DART recorded 23.1°C on July 10, 2015 (***Figure 21***), 21.5°C on August 5, 2014 (***Figure 24***), and 22.6°C on August 18, 2014 (***Figure 25***)

The above figures indicate that there is significant thermal gradient in the John Day reservoir and the McNary reservoir during warm summer days, but there is not a thermal gradient in The Dalles and Bonneville reservoirs. The difference in temperature in the John Day and McNary reservoirs is greater than 2°C so the water at depth can be viewed as cold water refuge relative to the surface temperatures on the days when the gradient exists. However, the cooler water deep in the reservoirs near the dams is generally not 2°C cooler than the main channel temperatures measured at the continuous monitors. Thus, the deep cooler water is not CWR relative to the main channel. Therefore, a better characterization is that the surface of the John Day and McNary Reservoirs warm due to warm air temperatures and solar radiation. This warming creates a temperature gradient relative to the main channel such that during warm periods, the top 3-5 meters (10-15 feet) is warmer than the main reservoir temperature.

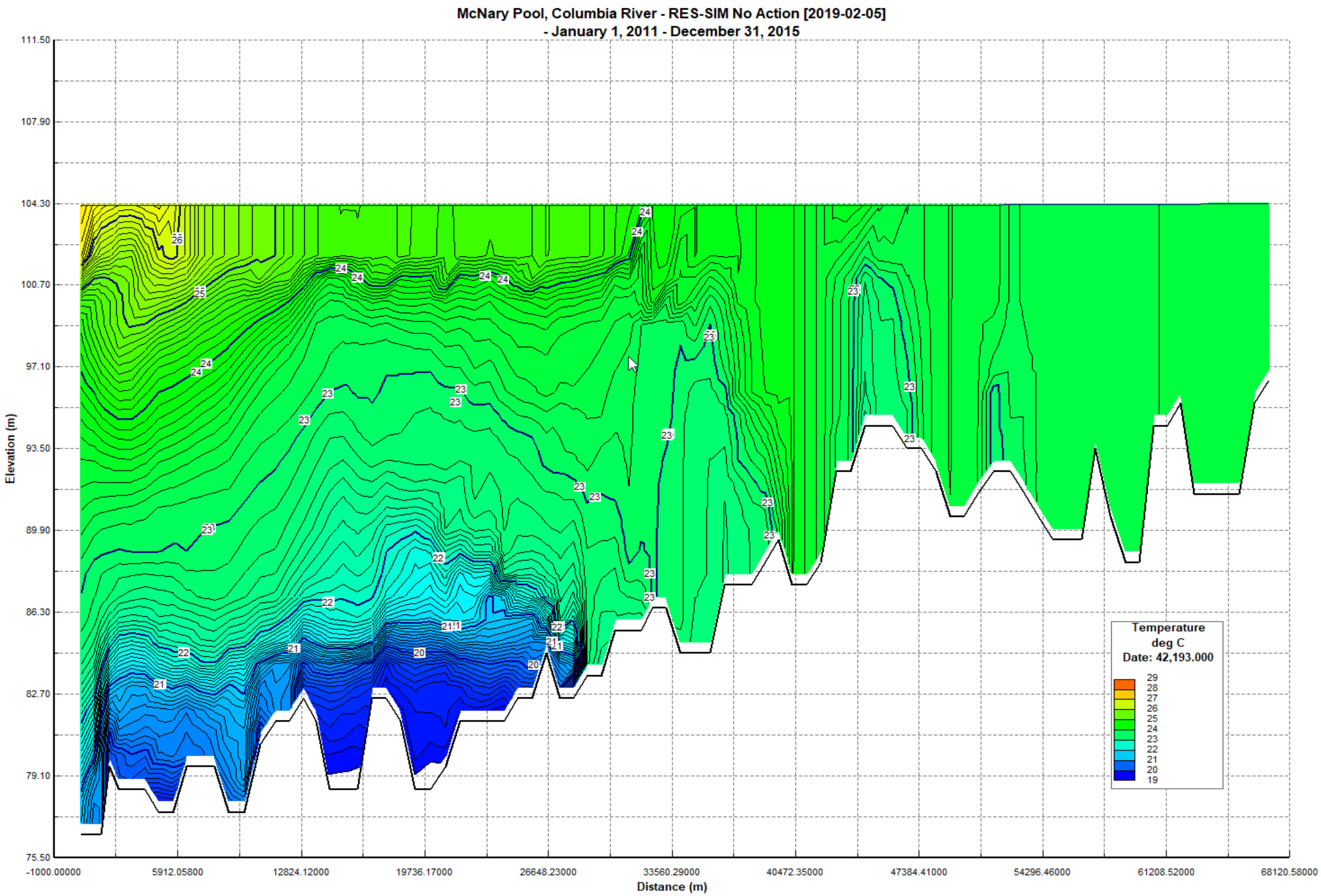

Figure 20 Two-Dimensional Model of McNary Reservoir Temperatures on July 8, 2015 (USACE, 2020)

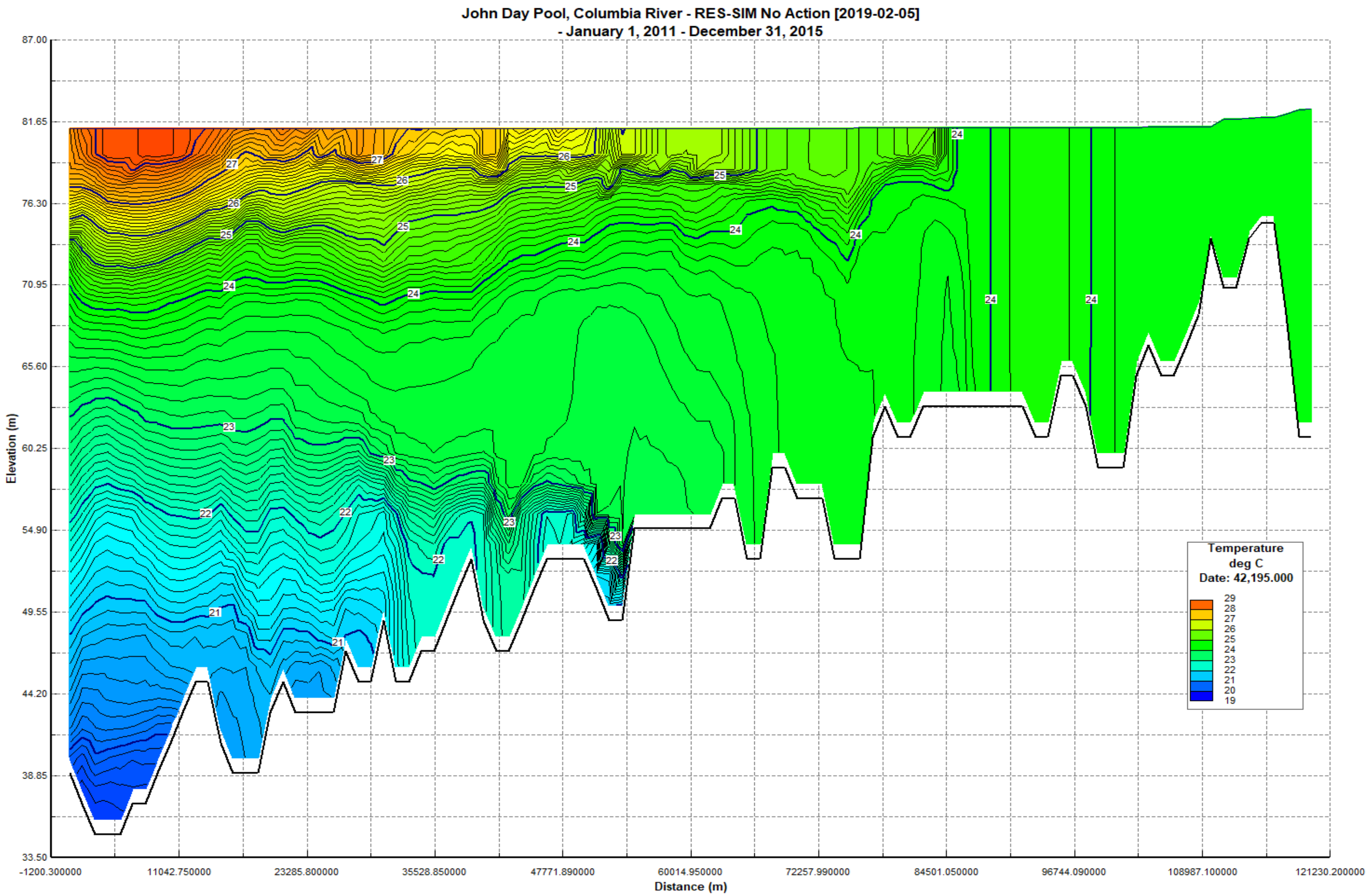

Figure 21 Two-Dimensional Model of John Day Reservoir Temperatures on July 10, 2015 (USACE, 2020)

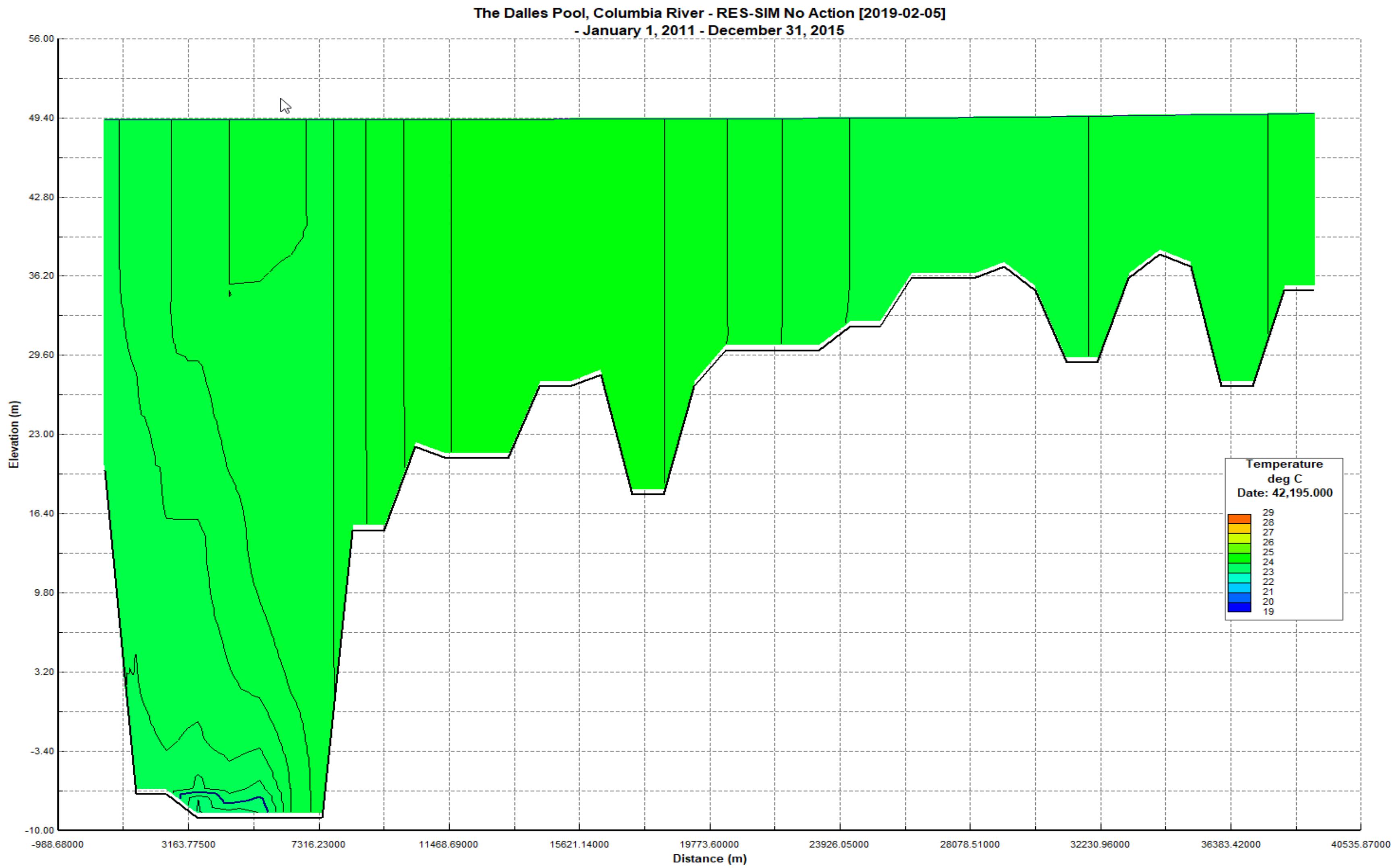

Figure 22 Two-Dimensional Model of The Dalles Reservoir Temperatures on July 10, 2015 (USACE, 2020)

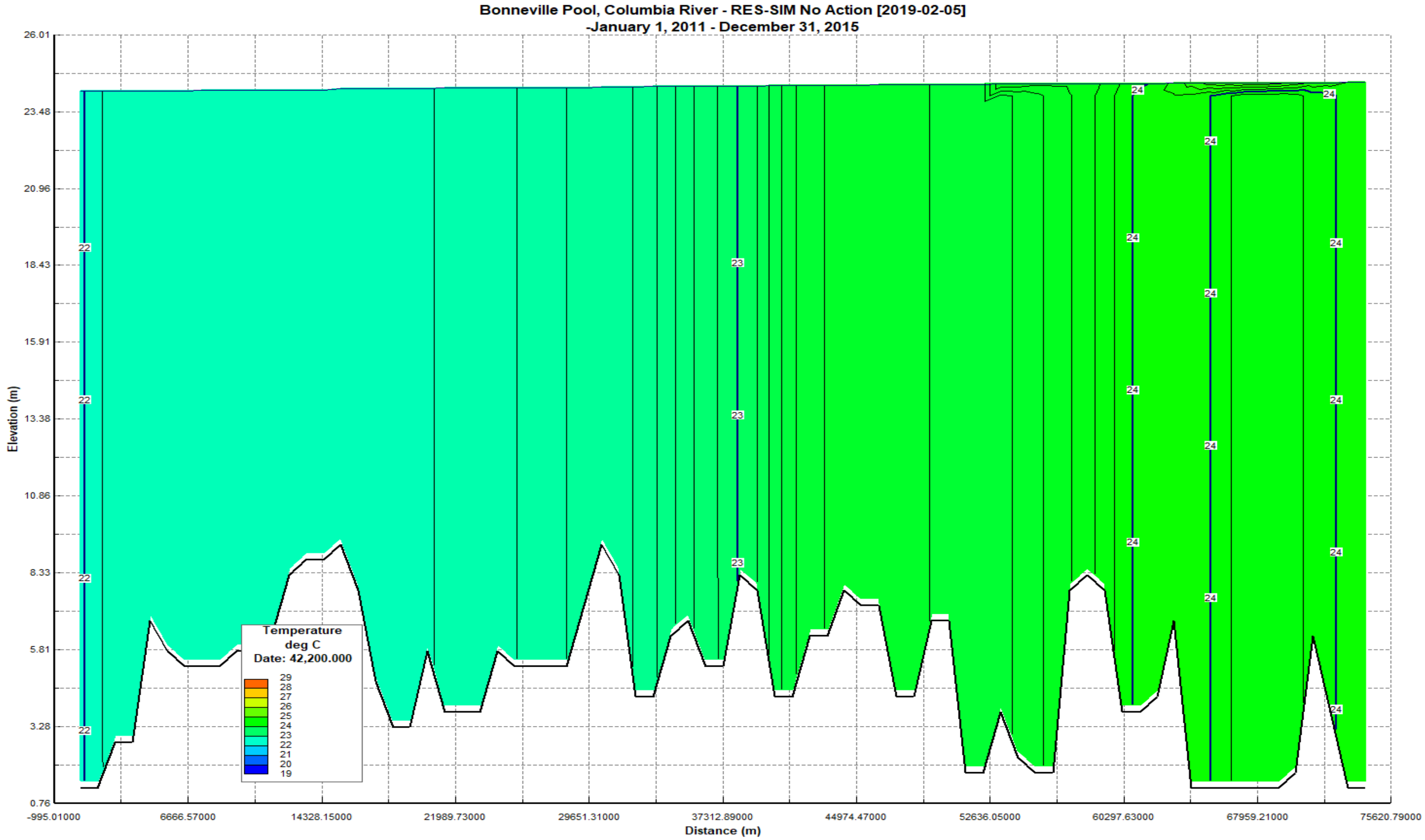

Figure 23 Two-Dimensional Model of Bonneville Reservoir Temperatures on July 15, 2015 (USACE, 2020)

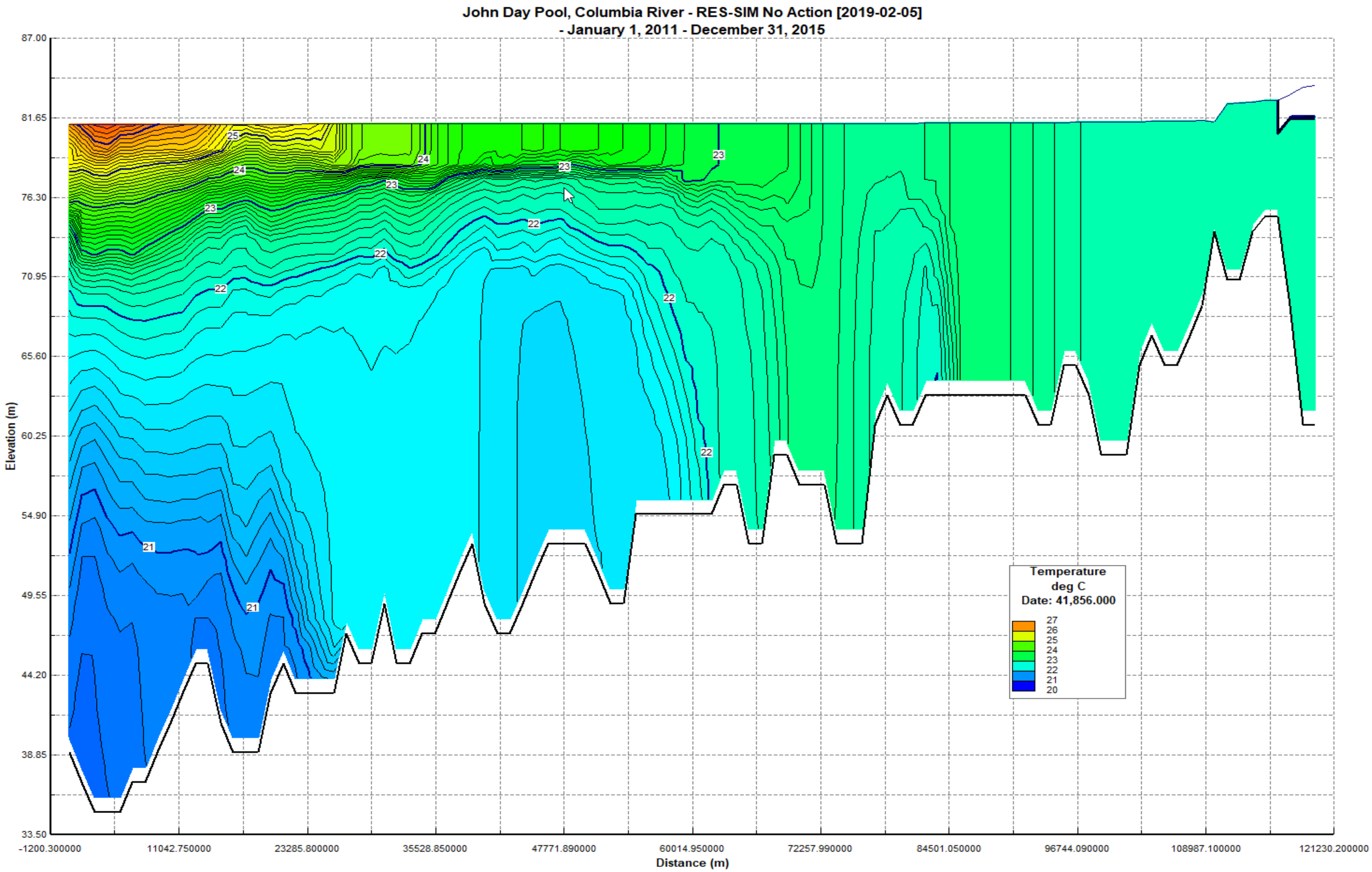

Figure 24 Two-Dimensional Model of John Day Reservoir Temperatures on August 5, 2014 (USACE, 2020)

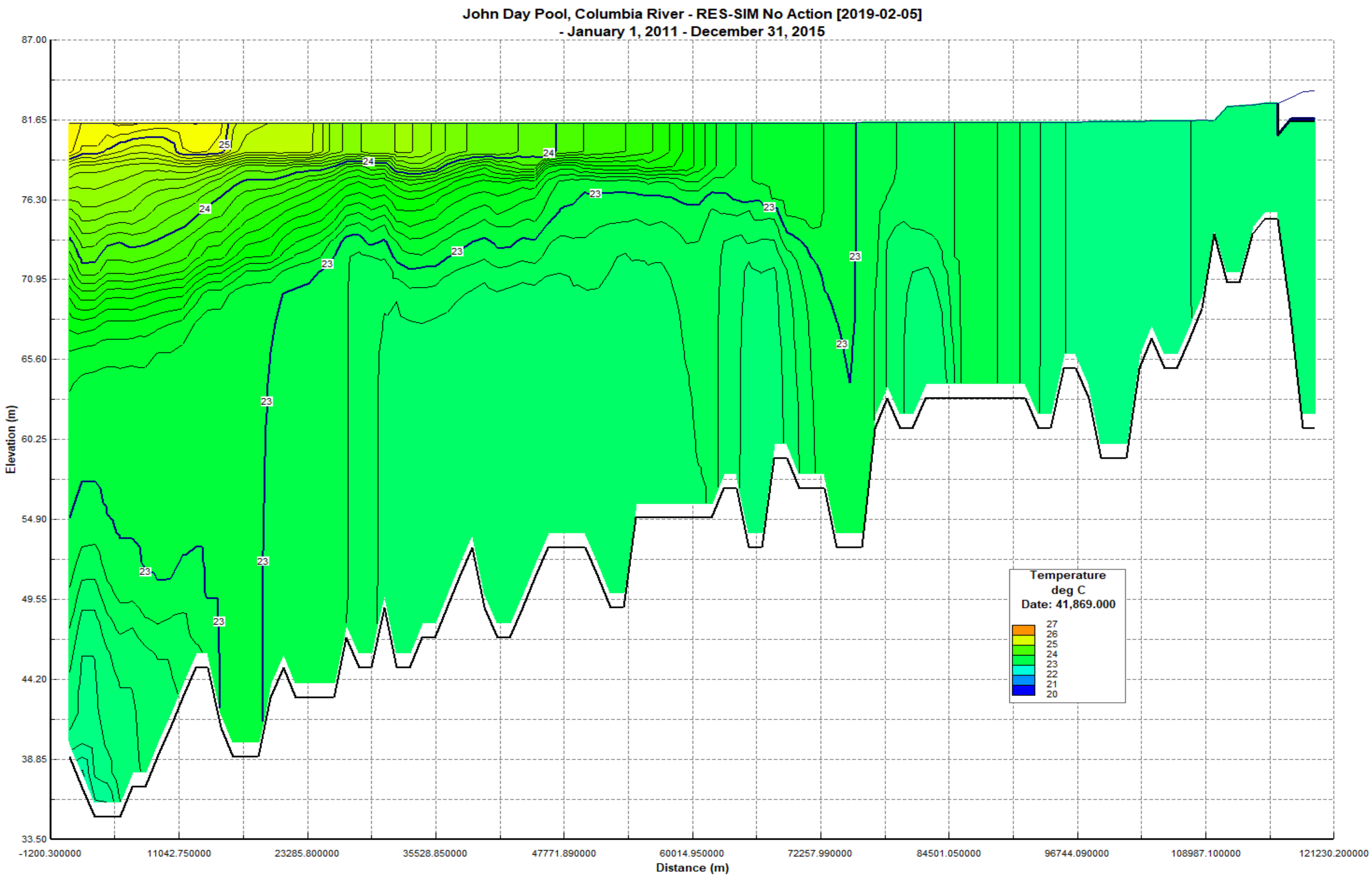

Figure 25 Two-Dimensional Model of John Day Reservoir Temperatures on August 18, 2014 (USACE, 2020)

Diurnal Temperature Variability in the Lower Columbia River

Figure*26** and ***Figure 27 show the range in temperature on certain days in the Bonneville and John Day forebays, respectively. Due to the large volume of water, there is only a small amount of daily variation in the Columbia River temperatures. During warm periods, the difference between the maximum and minimum temperature is less than 1°C, and typically about 0.2 – 0.5°C. Thus, there is no CWR in the Columbia River mainstem due to cooler nighttime temperatures.

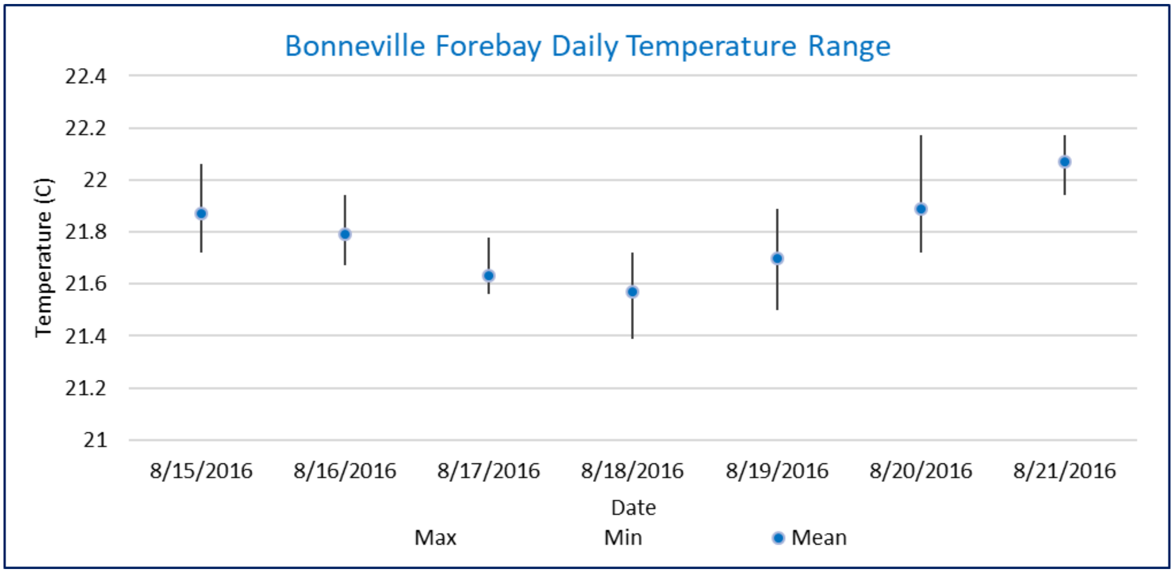

Figure 26 Bonneville Forebay Daily Temperature Range (DART)

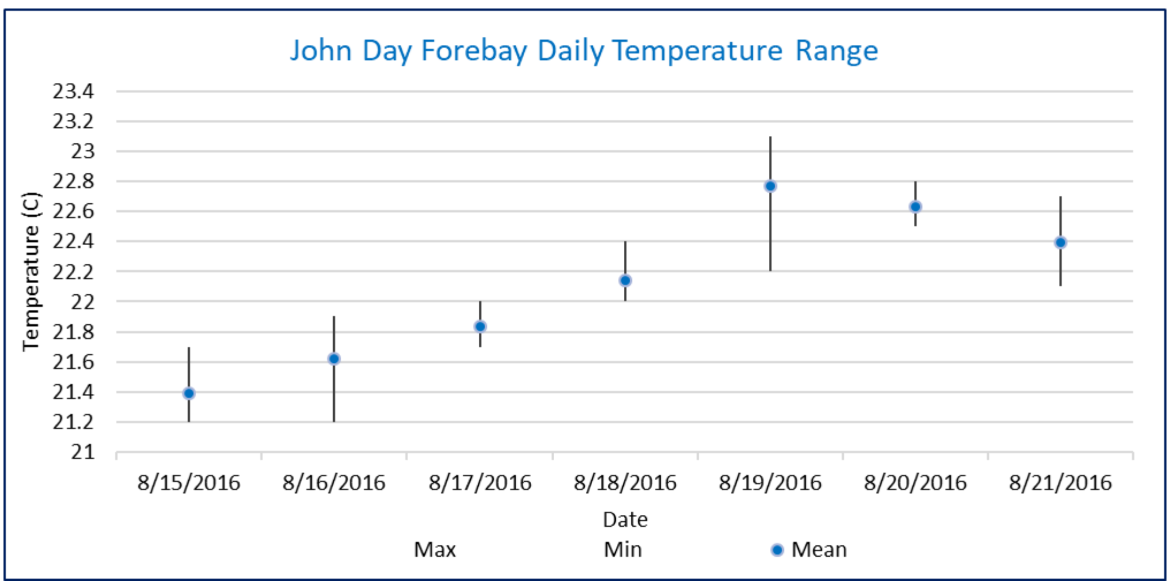

Figure 27 John Day Forebay Daily Temperature Range (DART)

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